VOLUME XLIX NUMBER 3

THE
JOURNAL OF GEOLOGY

April-May 1941

QUATERNARY GEOLOGY OF THE SAN ACACIA AREA, NEW MEXICO

CHARLES S. DENNY
Dartmouth College

ABSTRACT

At San Acacia the Rio Grande passes through a narrow canyon which separates the southern end of the broad Albuquerque-Belen Valley from the northern end of the Socorro Valley. Los Pinos Mountains lie to the east and the Sierra Ladron to the west. The Socorro Mountains separate the Socorro Valley from the higher Snake Ranch Flats and Magdalena Mountains to the west. Deformation in post–Santa Fe (post-Pliocene?) time produced the present basins and determined the location of the principal highlands and main drainage lines. In general, the mountain blocks are composed of relatively resistant pre-Tertiary rocks and Tertiary volcanic rocks, the lowlands of unconsolidated Tertiary basin deposits. The four pediment remnants present in the area and their projected grades above the present flood plains are:

	Feet
Ortiz (?) pediment	370–400
Tio Bartolo pediment	250
Valle de Parida pediment	150
Cañada Mariana pediment	50– 75

Their origin is discussed briefly. A cut-and-fill terrace at about 100 feet above the present flood plains is found in some places. The probable development by piracy in post-Ortiz time of the Rio Puerco and of the present course of the Rio Salado is discussed. Ancient and modern sand dunes and ventifacts, recent channel incision (arroyo cutting), and caliche on pediment surfaces are briefly mentioned.

INTRODUCTION

The Rio Grande depression[1] is bordered by mountains and plateaus whose present elevations still reflect the differential movements

[1] Kirk Bryan, "Geology and Ground-Water Conditions of the Rio Grande Depression in Colorado and New Mexico," *Regional Planning*, Part VI; *Rio Grande Joint Investigation in the Upper Rio Grande Basin* (Washington: National Resources Committee, 1938), Vol. I, Part II, sec. 1, p. 200, Fig. 49.

by which the depression was formed and the bordering areas uplifted. In central and northern New Mexico there are several pediments or erosion surfaces, the remnants of which slope outward from the bordering mountains to form a series of steps which descend toward the flood plains of the modern stream courses. These records of several successive positions of stabilized baselevel have been developed in valleys with through drainage—the Rio Grande and its tributaries. The details of the drainage and the minuteness with which soft rocks have been sorted out for reduction to lowlands depend on the length and number of these stages in the dissection of the region. There have also been episodes of alluviation. The recent incision of the channels or arroyos of the minor streams has, as elsewhere in southwestern United States, lowered the water table and furnished the silt which is deposited on the Rio Grande flood plain.

In central Socorro County near San Acacia a part of the Rio Grande depression, herein called the "San Acacia area," has a diversity of topographic forms that is in marked contrast to the simpler features of the wide central portions of the adjoining basins. During a study of the late Tertiary stratigraphy and structure of this area in 1935, 1936, and 1937,[2] much geomorphic information was gathered. As the writer does not expect to return to central New Mexico in the near future, this information is here presented. Heretofore, no geomorphic work has been done in this area except for brief descriptions by W. T. Lee[3] and by Bryan,[4] and the more detailed studies in the Socorro quadrangle, first by C. L. Herrick[5] and more recently by Bryan,[6] largely unpublished.

The major topographic features of the San Acacia area are shown on the topographic map of the state—scale 1:500,000[7]—a portion of

[2] C. S. Denny, "Tertiary Geology of the San Acacia Area, New Mexico," *Jour. Geol.*, Vol. XLVIII (1940), pp. 73–106.

[3] "Water Resources of the Rio Grande Valley in New Mexico," *U.S. Geol. Surv., Water Supply Paper 188* (1907).

[4] "Geology and Ground-Water Conditions . . . . ," *op. cit.*, pp. 197–225.

[5] "Clinoplains of the Rio Grande," *Amer. Geol.*, Vol. XXXIII (1904), pp. 376–81.

[6] "Pediments Developed in Basins with Through Drainage as Illustrated by the Socorro Area, New Mexico" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), pp. 128–29.

[7] *Topographic Map of New Mexico*, prepared by N. H. Darton (U.S. Geol. Surv., 1925).

which is reproduced here as Figure 1. Most of the area is included within the La Joya and Cerro Verde quadrangles for which only a rough topographic sketch, compiled by Darton on a scale of 1:125,000, is available. These maps lack sufficient detail to be useful in geomorphic study. Consequently, the geomorphic map (Fig. 2) and profiles (Fig. 3) are compiled from a plane-table survey and from aerial photographs except for a narrow strip along the southern

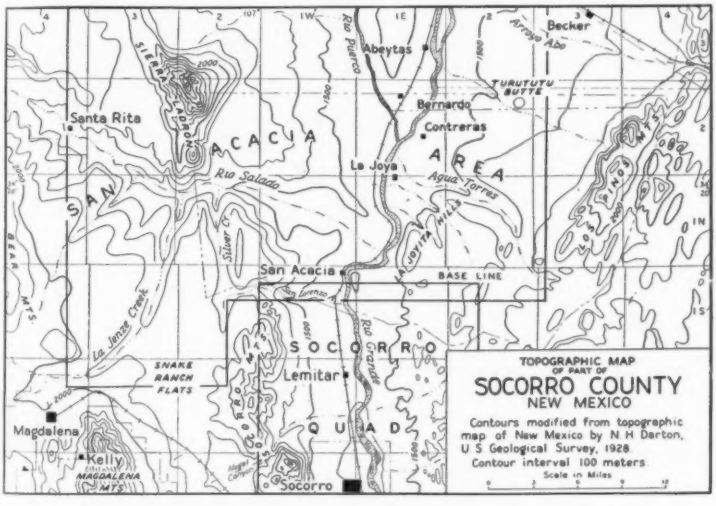


FIG. 1.—Topographic map of part of Socorro County, New Mexico

boundary of the area where the more detailed map of the Socorro quadrangle was used as a base. The delineation of the several dissected erosion surfaces or pediments is based on the tracing in the field of a given surface from place to place. Where this method is impossible, the identification of a given surface is based on its height above the flood plain of a major stream. The probable error in such a method is considerable. Only the broader features are delineated on the accompanying geomorphic map (Fig. 2). The transition slopes from the remnants of each higher surface to the remnants of each lower surface are included with the lower one. The amount of dissection of pediment remnants shown on Figure 2 is considerably less than that shown on plane-table sheets and aerial photographs

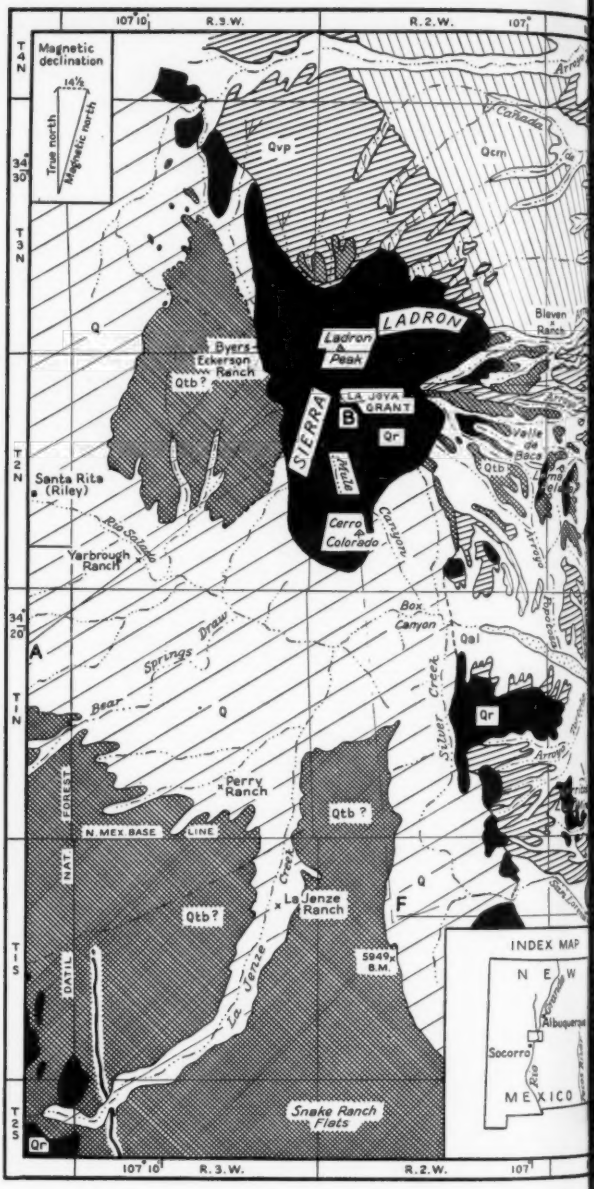
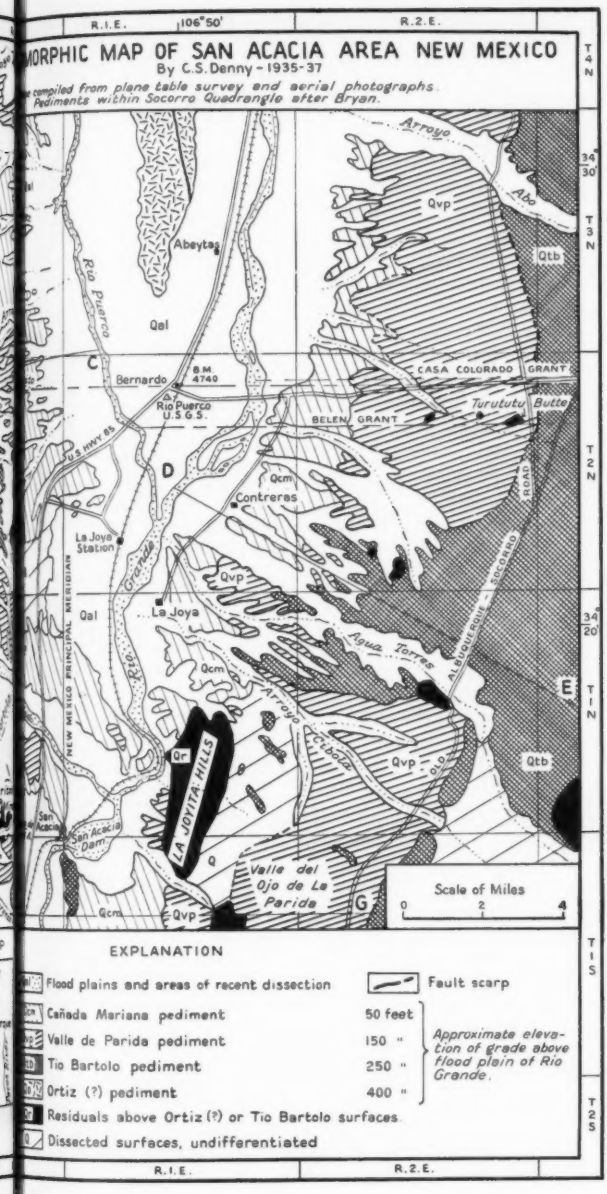


FIG. 2.—Geomorphic m[illegible]acia Area,



cacia Area, New Mexico

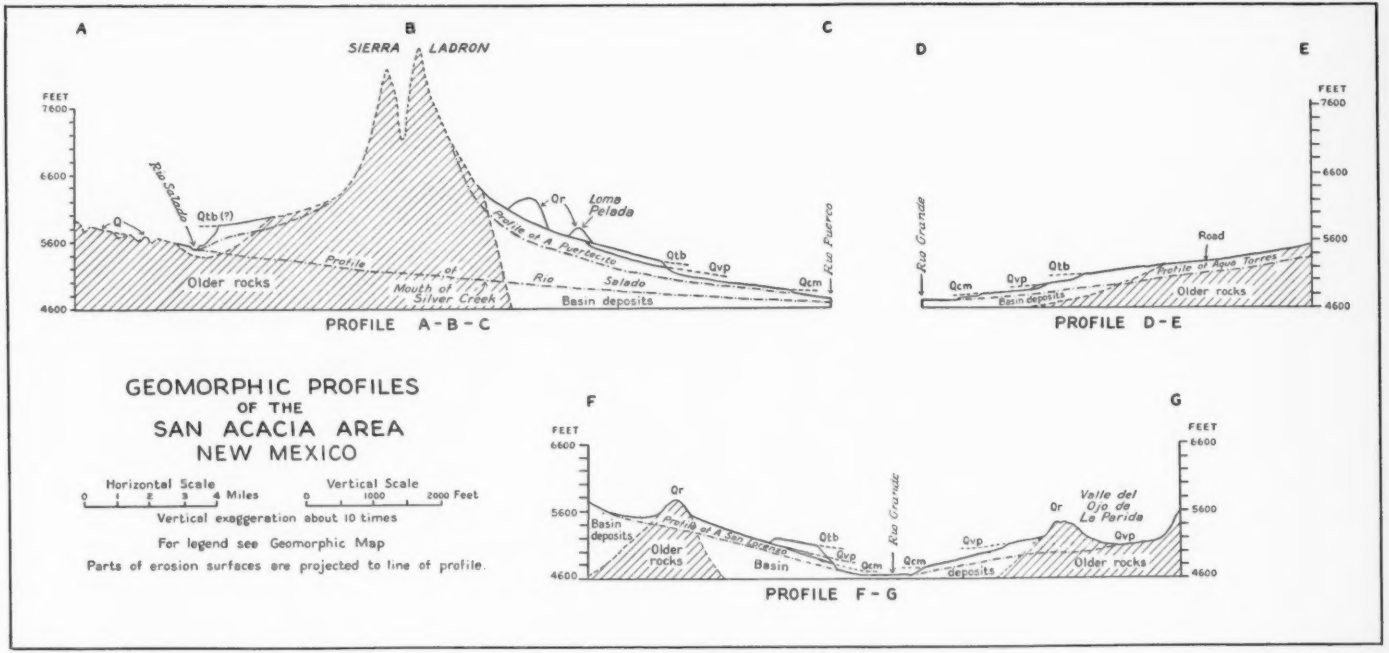


FIG. 3.—Geomorphic profiles of San Acacia Area, New Mexico

because the scale on which Figure 2 is reproduced is too small to portray the minute dissection actually present.

GENERAL GEOLOGY AND TOPOGRAPHY

PRINCIPAL TOPOGRAPHIC FEATURES

The San Acacia area includes the constriction where the Rio Grande, after flowing for scores of miles through the broad lowlands near Albuquerque and Belen (Fig. 4), is joined by the Rio Puerco and the Rio Salado, two of its principal tributaries, and passes through the narrow canyon at San Acacia to enter the northern end of the Socorro Valley (Fig. 1). Deformation in post–Santa Fe (post-Pliocene?) time uplifted Los Pinos and Socorro mountains and re-elevated the Sierra Ladron.[8] This deformation produced the present basins, which are somewhat narrower than the basins of Santa Fe (Pliocene?) time, and determined the location of the principal highlands and the main drainage lines of the present day. The Socorro Mountains were uplifted in the middle of the wide Socorro Basin of Santa Fe time.[9] This deformation produced the present narrow Socorro Valley to the east of the mountains and the higher and less-dissected basin of the Snake Ranch Flats to the west (Fig. 1).

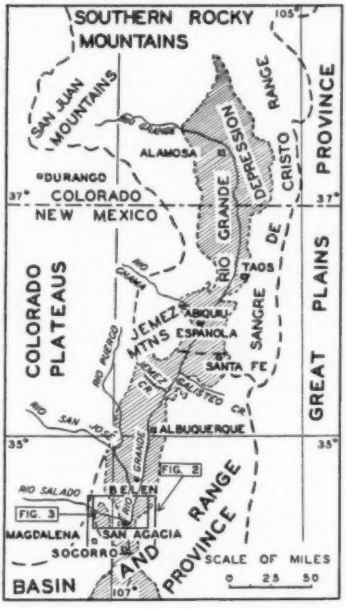


FIG. 4.—Index map. (On this map for Fig. 2 read Fig. 1, and for Fig. 3 read Fig. 2.)

To the west of the Rio Grande the Sierra Ladron rises to an elevation of about 9,200 feet (Fig. 1), whereas east of the Rio Grande Los Pinos Mountains reach only to about 7,700 feet above sea-level. The

[8] Denny, *op. cit.*

[9] *Ibid.*, Fig. 10.

Rio Grande flood plain at San Acacia is at an elevation of about 4,660 feet giving a maximum relief for the area of about 4,540 feet. The gradient of the river is 4 feet to the mile. The Socorro Valley to the south of San Acacia is 10–12 miles wide and lies between the Socorro Mountains (elevation 7,200 feet) on the west and low hills to the east.[10] The several pediment remnants rise steplike from the flood plain of the Rio Grande toward the bordering highlands.

To the west of the Sierra Ladron–Socorro Mountain axis plateau-like remnants of pediments border the Rio Salado, La Jenze Creek, and their tributaries (Fig. 2). These areas slope in general toward the main drainage lines and lie at elevations of from 5,900 to 6,200 feet. Stream courses have been cut as much as 700 feet below that level. One of these remnants—the Snake Ranch Flats (Fig. 1)—lies at an elevation of about 6,000 feet, more than 1,500 feet above the Rio Grande at Socorro. Part of the area of the Flats has no external drainage and is being built up by silt and sand brought in by streams from the adjacent plains and from the Magdalena Mountains to the southwest. Streams which flow eastward from the Magdalena Mountains, south of the main area of the Flats, pass through the Socorro Mountains in Nogal, Blue, and Milk Ranch canyons (see Socorro quad.) to join the Rio Grande near Socorro. The plateau to the north of the Rio Salado (Fig. 2; T. 2 and 3 N., R. 3 W.) between Santa Rita and the Sierra Ladron has local undrained areas although considerably dissected.

INFLUENCE OF LITHOLOGY AND STRUCTURE[11]

The Sierra Ladron, Los Pinos, and Magdalena mountains (Fig. 1) are held up by granite, gneiss, and similar rocks of pre-Cambrian age which are overlain on the flanks of the ranges by sedimentary rocks of late Paleozoic age.[12] Lowlands near Santa Rita and to the southeast of La Joyita Hills are underlain by late Paleozoic and Mesozoic sedimentary rocks. The Bear and Socorro mountains, La Joyita Hills, and the Cerritos de Las Minas (Fig. 2) are composed pre-

[10] See also the Socorro quadrangle (U.S. Geol. Surv.).

[11] Denny, *op. cit.* Figs. 1 and 3 of this paper cover the same area. These two maps should be compared when reading the following paragraphs.

[12] Darton, " 'Red Beds' and Associated Formations in New Mexico," *U.S. Geol. Surv. Bull. 794* (1928), Pls. 17 and 26; Denny, *op. cit.*, Fig. 6.

dominantly of volcanic rocks (flows and tuffs) of Tertiary (Miocene?) age.

The late Tertiary basin deposits (Popotosa and Santa Fe formations) vary from bouldery gravel to *playa* clay. To the east of the Sierra Ladron, along the Arroyos Popotosa and Yeso (T. 1 and and 2 N., R. 1 and 2 W.), clay and silt of the Popotosa formation have been carved into badlands. Partly cemented bouldery gravel in the Santa Fe formation holds up the Loma Pelada (T. 2 N., R. 1 W.).

FIG. 5.—Alluvium resting on surface of Valle de Parida pediment which bevels eastward-dipping Popotosa beds. Exposure in north bank of San Lorenzo Arroyo to southwest of Cerritos de Las Minas.

The pediment remnants are covered with alluvium (Fig. 5) which near the higher mountains is a bouldery gravel but near the main drainage lines is a pebbly gravel or coarse sand. Most of this material is a stream deposit; some of the sand may be wind borne. The stones in the alluvium are angular and subangular except for a few rounded pebbles derived from conglomerates in the older rocks. In many areas the alluvium is cemented to form resistant beds of caliche, such as the plateau-like remnant of the Tio Bartolo pediment between Santa Rita and the Sierra Ladron (Fig. 2; T. 2 and 3 N., R. 3 W.) which is indented by steep-sided canyons with rounded

heads. The pediment alluvium varies from 1 to 35 feet in thickness with 10 feet as an average figure. The thickest sections of this alluvium may represent a slight filling of the basin during the formation of the erosion surface on which the alluvium rests.

DRAINAGE

In the Albuquerque-Belen Valley the Rio Grande follows a course which is somewhat to the east of the geographic center of the lowland. At Bernardo the Rio Grande is joined on the west by the Rio Puerco and just north of San Acacia by the Rio Salado. Both are pirate streams, the origin of which is discussed in a later paragraph.

The drainage pattern developed on the pre-Tertiary rocks of the Sierra Ladron is more or less radial (Fig. 2). A northward-flowing stream from Ladron Peak follows a circular course as it turns more and more to the east to join the Rio Puerco as an eastward-flowing stream. On the east side of the Rio Grande the drainage consists of more or less parallel streams which flow in a westerly and northwesterly direction to the Rio Grande. Minor streams or arroyos, where dissecting a pediment remnant, form a succession of long, narrow, parallel ridges and give rise to parallel and to pinnate drainage patterns.[13]

CLIMATE AND VEGETATION

The San Acacia area has a semiarid climate with a mean annual rainfall of about 10 inches a year in the valleys, increasing to about 20 inches a year on the summits of the Sierra Ladron and Los Pinos mountains. The distribution of the rainfall is seasonal with the maximum precipitation in July and August.[14]

Most of the area is a grassland.[15] Desert shrubs, cactuses, and

[13] E. R. Zernitz, "Drainage Patterns and Their Significance," *Jour. Geol.*, Vol. XL (1932), pp. 498–521.

[14] R. J. Martin, "Climatic Summary of the United States, Sec. 27," *U.S. Dept. Agric., Weather Bur.* (1933); C. K. Cooperrider and B. A. Hendricks, "Soil Erosion and Stream Flow on Range and Forest Lands of the Upper Rio Grande Watershed in Relation to Land Resources and Human Welfare," *U.S. Dept. Agric., Tech. Bull. 576* (1937); see also *Regional Planning*, Part VI: *Rio Grande Joint Investigation in the Upper Rio Grande Basin* (Washington: National Resources Committee, 1938), Vol. I, Part I, sec. 2, Appen. A, and Pl. III.

[15] Cooperrider and Hendricks, *op. cit.;* V. Bailey, "Life Zones and Crop Zones of New Mexico," *U.S. Dept. Agric., North Amer. Fauna No. 35* (1913), Pl. I.

yuccas are abundant. Cottonwood and willow abound near the Rio Grande, as does the recently introduced tamarisk which grows rapidly and serves as an important factor for the stabilization of silt on the flood plain. In the Sierra Ladron, Los Pinos, and Bear mountains, and along the upper Rio Salado to the west of Silver Creek (Fig. 2; T. 1 N., R. 2 W.) juniper and piñon form woodlands with grassy vegetation more or less abundant between the trees dependent on the slope and soil conditions. Small areas of pine-fir forest are present near the summit of Magdalena and Los Pinos mountains and Sierra Ladron.

THE ORTIZ SURFACE

Deformation in post–Santa Fe (latest Pliocene to early Pleistocene?) time re-elevated the Sierra Ladron and, at the same time, created the Socorro and Los Pinos mountains (Fig. 1) within the area of the basins in which the Santa Fe formation had been deposited throughout much of the Pliocene epoch.[16] Following this post–Santa Fe uplift, which was general throughout much of the Rio Grande depression, the Rio Grande cut down an unknown distance through these basin deposits until it became more or less stabilized at a level which, in the Albuquerque-Belen Valley, lies from 450 to 500 feet above the present flood plain. The grades of the tributaries were thus stabilized, and a very extensive surface was cut across the more or less deformed basin deposits and locally across the mountain blocks. Remnants of this surface are called "Ortiz"[17] from the pediment remnants which surround the Ortiz Mountains and were first described by Ida H. Ogilvie.[18]

In the Albuquerque-Belen Valley the most extensive pediment remnant correlated with the Ortiz is the Llano de Albuquerque, a mesa 70 miles long and from 1 to 14 miles wide which lies between the Rio Puerco and the Rio Grande.[19] This mesa extends from Jemez

[16] Denny, *op. cit.*

[17] Bryan, "Geology and Ground-Water Conditions . . . . ," *op. cit.*, p. 215 and Fig. 49.

[18] "The High-Altitude Conoplain: A Topographic Form Illustrated in the Ortiz Mountains," *Amer. Geol.*, Vol. XXXVI (1905), pp. 27–34.

[19] Kirk Bryan and F. T. McCann, "The Ceja del Rio Puerco: A Border Feature of the Basin and Range Province in New Mexico, II: Geomorphology," *Jour. Geol.*, Vol. XLVI (1938), Fig. 2.

Creek southward almost to Bernardo where it is only from 370 to 400 feet above the Rio Grande flood plain. The mesa (T. 3 N., R. 1 E.) is shown as Ortiz(?) on Figure 2. It is uncertain whether this loss in elevation is the result of a southward inclination of the mesa surface or whether the mesa top in this area represents a pediment remnant which is lower and younger than the level of the Llano to the west of Albuquerque. The possibility that recent faulting can account for some of this decrease in elevation will be considered in a later paragraph. There are no other pediment remnants within the San Acacia area which can with any degree of probability be referred to Ortiz time. With the completion of the Ortiz surface the Rio Grande attained approximately its present course. The asymmetric position of the river in the Albuquerque-Belen Valley (Fig. 4) is perhaps due to the relatively large size of the tributaries which enter it from the west.

THE TIO BARTOLO SURFACE

In the San Acacia area the oldest erosion surface of which any extensive remnants are preserved is called the "Tio Bartolo pediment." The projected grade of these remnants lies about 250 feet above the present flood plains—a height which corresponds to that of the Tio Bartolo pediment in the Socorro quadrangle to the south.[20] On the east side of the Rio Grande to the north of the Aqua Torres (Fig. 2) are extensive pediment remnants which are a part of the Tio Bartolo surface. These remnants of the pediment are preserved primarily because they are largely cut on the older and slightly more resistant rocks. Near the western margin of these remnants the surface crosses deformed basin deposits of Santa Fe age[21] (Fig. 3, profile *D–E*) and has locally been dissected. Profile *D–E* shows that the western part of the surface near the Aqua Torres has a steeper westward slope than that portion which lies to the east. It is probable that this break in slope is related to the change from older rocks (largely Mesozoic sediments) to basin deposits. Perhaps the steeper-sloping remnant is part of a younger surface. The well-defined rem-

[20] Bryan, "Pediments Developed in Basins . . . . ," *op. cit.*, pp. 128–29.

[21] Denny, *op. cit.*, Fig. 1.

nants at the north end of the Valle del Ojo de La Parida (T. 1 S., R. 2 E.) are cut largely across Cretaceous rocks and are capped by caliche. A part of La Joyita Hills are the much-dissected remnants of the Tio Bartolo surface.

On the west side of the Rio Grande and to the north and east of the Sierra Ladron there are a few small pediment remnants of the Tio Bartolo surface (Figs. 3, 6, 7, and 8). These remnants have steep gradients—locally as much as 250 feet to the mile—and are capped by a bouldery gravel which is composed of angular fragments of granitic rock as much as 4 feet in diameter.

FIG. 6.—View looking southwestward across remnants of Valle de Parida pediment (south of Valle de Baca) and of Tio Bartolo pediment (in middle distance) to the Cerro Colorado.

The erosion surfaces in the area to the west and south of the Sierra Ladron, including the Snake Ranch Flats, were not mapped in detail. However, extensive pediment remnants tentatively correlated with the Tio Bartolo surface are shown on the geomorphic map (Fig. 2). The remnant between La Jenze and Silver creeks is mantled by a thick bed of caliche and extends southward along the east side of the Snake Ranch Flats. The westward slope of this remnant, if projected to the east, would pass over the top of the Socorro Mountains. This surface, therefore, has probably been tilted westward since its formation by a recent uplift of the Socorro Mountains. Remnants of the Tio Bartolo pediment are also found to the west of La Jenze Creek. To the west and southwest of the Snake Ranch Flats the Tio Bartolo pediment is buried beneath the alluvial slopes which border the Magdalena Mountains (Fig. 1).

The caliche-capped mesa to the west of the Sierra Ladron is about

350 feet above the Rio Salado.[22] The surface of the mesa rises to the north and can be traced to within a mile or two of the western edge

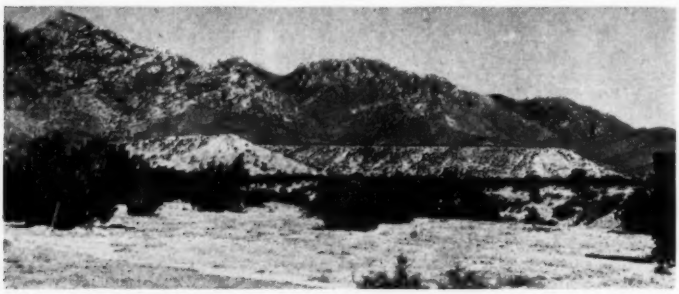


FIG. 7.—View looking northwest across the surface of Valle de Parida pediment to mesas (in middle distance) which represent the Tio Bartolo pediment. North end of Sierra Ladron in background.

FIG. 8.—View looking southeastward across Valle de Parida pediment to Ladron Peak. A fan-shaped remnant of Tio Bartolo pediment lies at foot of the peak.

of remnants of the Valle de Parida pediment (Fig. 2; T. 3 N., R. 2 and 3 W.), which lie at a somewhat lower altitude. Therefore this mesa to the north of the Rio Salado is correlated with the Tio Bar-

[22] *Ibid.*, Fig. 9.

tolo surface. The somewhat greater height of this Tio Bartolo pediment remnant above the Rio Salado as compared with other remnants of the same surface elsewhere is due to the lowering of the channel of the Rio Salado by piracy.

PIRACY OF THE LOWER RIO PUERCO

The Rio Puerco, one of the principal tributaries of the Rio Grande in New Mexico, follows a general north-south course for about 140 miles. For about 70 miles north from Bernardo the Rio Puerco is separated from the Rio Grande by a westward-facing escarpment—the Ceja del Rio Puerco—which bounds the western edge of the Llano de Albuquerque. Bryan and McCann[23] have shown that the Llano is a remnant of the Ortiz surface and that the lower Rio Puerco was not then in existence. These authors state that the main drainage of the present upper Rio Puerco Valley was carried by a hypothetical stream—the Rio Chacra—which headed in Haynes Flat to the west of Cuba and flowed southward and southeastward through the Mesa Prieta across the Ceja del Rio Puerco and the Llano de Albuquerque to join the Rio Grande near Los Lunas. The piracy by which the Rio Puerco (to the north of its junction with the Arroyo Chico) was developed from the ancestral Rio Chacra is described by the same authors in an earlier paper.[24] The lower Rio Puerco is probably also the result of piracy although the mechanism is not clear. "The capturing . . . . was probably done by a northerly tributary to a westerly tributary of the ancestral Rio Grande. This westerly tributary flowed eastward and entered the river at or near the mouth of the present Rio Puerco."[25] These authors further suggest that this second-order (northerly) tributary worked headward (to the north) in the weak Santa Fe beds and beheaded the drainage of the present Rio San José and finally that of the hypothetical Rio Chacra. The length of the present Rio Puerco from its junction with the hypothetical Rio Chacra to Bernardo is about twice that of the Rio Chacra from this junction to the ancestral Rio Grande of Ortiz

[23] "The Ceja del Rio Puerco . . . . ," *op. cit.*, Fig. 2.

[24] Bryan and McCann, "Successive Pediments and Terraces of the Upper Rio Puerco in New Mexico," *Jour. Geol.*, Vol. XLIV (1936), pp. 160–64.

[25] Bryan and McCann, "The Ceja del Rio Puerco . . . . ," *op. cit.*, pp. 13–14.

time, according to the reconstruction of Bryan and McCann.[26] It is possible that inter–Santa Fe volcanic rocks exposed near Isleta[27] retarded the downcutting of the Rio Grande and the hypothetical Rio Chacra so that the ancestral Rio Puerco was able to cut headward more rapidly and at a lower elevation than the Rio Chacra. Post-Ortiz lava-flows to the west of Los Lunas may also have retarded this downcutting.

Post-Ortiz deformation may also have been important in the development of the lower Rio Puerco. The remnant of the Ortiz(?) pediment to the north of Bernardo (Fig. 2; T. 3 N., R. 1 E.) is broken by a northward-trending escarpment about 40 feet high which faces westward. This escarpment strikes parallel to a fault which is exposed at the eastern edge of the mesa and is a fault or possibly a fault-line scarp. This fault appears to have displaced the cap of caliche which mantles the pediment surface. Figure 9 is a view looking northward toward the fault plane (under man). To the west (left) of the plane about 15–20 feet of caliche underlies the mesa. Sand and silt (Santa Fe formation) lie unconformably beneath the caliche. The fault plane is marked by a sand dike about 6 inches wide which strikes north 3°–4° west and dips at an angle of 75° to the west. The beds are locally dragged up along the fault. This break is probably a normal fault with the downthrown side on the west. No caliche is found on top of the pinnacles to the east of the fault (to right in Fig. 9). The last movement along this fault is post-caliche and, therefore, post-Ortiz. This inference rests on the assumption that the caliche is a sure indicator of the Ortiz surface, but so much is unknown regarding caliche that this inference may not be wholly justified. Its absence on the east side of the fault plane might possibly be related to differences in the composition or the hydrology of the rocks on either side of the plane so that caliche formed only on the west.

The westward-facing escarpment is, therefore, probably but not surely a fault scarp. To the west of this scarp there is a north-south depression parallel to the scarp which is from a quarter to half a mile wide. It is bounded on the west by a much gentler and more irregu-

[26] *Ibid.*, Fig. 2.

[27] Bryan, "Geology and Ground-Water Conditions . . . . ," *op. cit.*, Fig. 49.

lar eastward-facing slope not more than 20 feet high. This depression may be in part the result of stream erosion which was localized by the scarp. Perhaps it is an old channel of the Rio Puerco, although no river gravel such as should be carried by the Puerco is exposed at the edge of the mesa.

FIG. 9.—Normal fault displacing caliche cap at eastern edge of remnant of Ortiz(?) pediment to northwest of Abeytas. Man on skyline is seated on fault plane. Beds of caliche (to left of man) are light colored and rest unconformably upon the Santa Fe formation.

This escarpment, if projected northward, more or less follows the western edge of the Llano de Albuquerque for some distance. Such a scarp might have ponded the small streams which in Ortiz time flowed eastward across the Llano to the Rio Grande. Such ponds would drain southward toward a northward-heading, second-order tributary of a first-order tributary entering the Rio Grande near Bernardo. In such a manner the ancestral lower Rio Puerco may have been able to behead the Rio Chacra and develop the present lower Rio Puerco.

This interpretation seems to postulate somewhat inadequate causes for a major change in drainage. If, however, the fault scarp be considered the most easterly and one of the smallest faults of a group, then a ready explanation is at hand. As shown in the hypothetical map and section (Fig. 10), a shallow graben could have been formed in late Ortiz time without leaving marked evidence. This graben could easily have diverted the easterly drainage of Ortiz time into the southward-flowing late Ortiz Rio Puerco. Such diversion would have made the latter the most powerful stream of the region during the ensuing post-Ortiz period of dissection.

THE VALLE DE PARIDA SURFACE

The remnants of the Tio Bartolo pediment are bordered by the remnants of a lower and younger surface whose gradient, if projected to the Rio Grande, lies about 150 feet above the flood plain (Fig. 3). The slightly dissected Valle del Ojo de La Parida (Fig. 2; T. 1 S., R. 1 and 2 E. See also Socorro quad.) is a remnant of this surface.[28] Other remnants are found on the east side of the Rio Grande along the Arroyo Cibola and near Turututu Butte. A broad surface to the north of Ladron Peak (Fig. 8) is assigned to Valle de Parida time. Both to the north and to south of the Rio Salado, along Arroyos Popotosa (Fig. 6) and Tortola, and near the Cerritos de Las Minas there are extensive remnants of the Valle de Parida pediment. The Valle de Parida surface was not differentiated in the area to the west of Sierra Ladron and Silver Creek.

PIRACY OF THE LOWER RIO SALADO

The Rio Salado has probably come into existence through piracy. There is considerable evidence to indicate that the ancestral Rio Salado, at the Tio Bartolo stage, flowed to the southeast from Santa Rita across the Snake Ranch Flats and entered the Rio Grande to the south of Socorro (Fig. 1). During Valle de Parida time a stream following the course of the lower Rio Salado (to the east of Silver Creek) cut headward (westward) through the Sierra Ladron–Socorro Mountain divide and diverted the ancestral Rio Salado from its southerly course to that of the present day.

[28] Bryan, "Pediments Developed in Basins . . . . ," *op. cit.*, pp. 128–29.

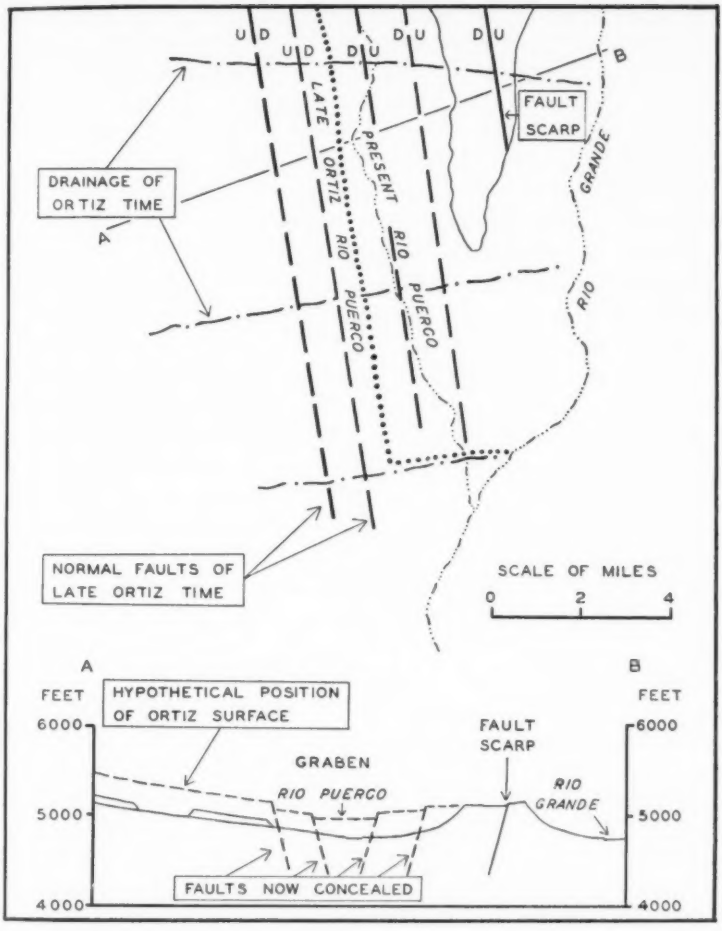


FIG. 10.—Hypothetical map and section to show possible origin of Rio Puerco

In like manner San Lorenzo Arroyo and Puertocito de Canyoncito de Lemitar (Fig. 1 and Socorro quad.) have cut westward through the Socorro Mountains and are beheading small westward-flowing streams on the Snake Ranch Flats. Nogal Canyon, Blue Canyon, and Milk Ranch Canyon drain not only the Flats but also the Magdalena Mountains. The lower Rio Salado, to the east of Silver Creek (Fig. 2; T. 1 N., R. 2 W.), cut headward (westward) faster than did the other eastward-flowing streams of the Sierra Ladron–Socorro Mountain axis. This headward cutting took place in a structural gap between the north end of the Tertiary volcanic rocks of the Socorro Mountains and the pre-Cambrian crystalline rocks of the Sierra Ladron.[29] The Tertiary volcanics hold up the residuals to the east of Silver Creek (Fig. 2) and end just south of the Rio Salado. The only part of the Ladron block actually cut by the Salado is a narrow prong of limestone. The process was also facilitated by better water supply. The Sierra Ladron at present receives more rainfall than the Socorro Mountains, and probably such a relationship was also true during Valle de Parida time. Thus the lower Rio Salado had a greater yearly flow than did the arroyos to the south. La Jenze Creek (Figs. 1 and 2; T. 1 S., R. 3 W.) was formed by a southern tributary of the Salado that by headward erosion from the Salado Canyon committed piracy on a stream which flowed eastward from the gap between the Magdalena and Bear mountains.

The thick mantle of caliche which caps the northern part of the remnant of the Tio Bartolo pediment that lies between La Jenze and Silver creeks gives evidence favoring the hypothesis that the ancestral Rio Salado flowed southward through the Snake Ranch Flats. As brought out in a later paragraph, the relatively great thickness of caliche on top of some pediment remnants is due to the fact that the ephemeral streams which flowed over these surfaces came from a limestone region. The mantle of caliche in the area in question (between La Jenze and Silver creeks) decreases in thickness toward the south; and it seems probable, therefore, that the streams which cut this erosion surface came from the north. The nearest source of limestone is the area between the Rio Salado and the Cerro Colorado.[30]

[29] Denny, *op. cit.*, Fig. 1.

[30] *Ibid.*, Fig. 6.

Therefore, it is thought that during Tio Bartolo time streams flowed southward from this area to the present remnant of the Tio Bartolo pediment between La Jenze and Silver creeks. At such a time the present Rio Salado was not in existence.

THE *Cañada* MARIANA SURFACE

The Valle de Parida pediment is bordered by remnants of the still lower and younger *Cañada* Mariana surface which flanks the abandoned flood plains of the present arroyos and the Rio Grande. The projected gradient of this pediment lies about 50–75 feet above the river (Figs. 2 and 3). This surface was not recognized by Bryan[31] in the Socorro quadrangle where it is apparently masked by a cut-and-fill terrace, the top of which in the vicinity of Arroyo Nogal is about 100 feet above the present arroyos. Extensive remnants of the *Cañada* Mariana pediment are found between the Rio Puerco and the Sierra Ladron, along Arroyos Yeso and Puertocito and the *Cañada* de Mariana Chavez. Also on the east side of the Rio Grande there are numerous *Cañada* Mariana remnants bordering the present flood plain. The *Cañada* Mariana pediment was not differentiated in the area to the west of Sierra Ladron and Silver Creek.

CUT-AND-FILL TERRACES

Along the Rio Salado from the mouth of Silver Creek eastward for about 4 miles are several gravel-covered mesas (not shown on Fig. 2) standing about 100 feet above the present arroyo. These mesas are remnants of a cut-and-fill terrace as shown in Figure 11. The top of this fill is partially cemented by calcium carbonate and is somewhat above the level of the neighboring remnants of the *Cañada* Mariana pediment. Extensive areas of uncemented fill are also found in the valley of Silver Creek, where the alluvium underlies a surface at least 50 feet above the creek. It is probable that this fill is of the same age as the 100-foot fill found along the Rio Salado. Figure 11 shows that the top of the Rio Salado fill is about 100 feet above the arroyo, whereas to the north and south the land has been reduced to the level of the *Cañada* Mariana pediment.

This fill records a downcutting by the Rio Salado at least to the

[31] *Op. cit.*

level of the present arroyo bottom, followed by a filling-in of the channel to a depth of more than 100 feet. Salts are deposited today in the channel of the Salado, as the name implies. When the Rio Salado was flowing on top of the fill it cemented the gravel in its channel, whereas the fill to the north and south was only slightly cemented because the side streams do not drain limestone areas as does the Salado. Thus the fill is preserved along the channel of the present arroyo, whereas to the north and south it has been removed in the erosion which produced the *Cañada* Mariana pediment and finally the modern arroyos. This fill is probably the equivalent of the cut and fill terrace of the Socorro quadrangle.

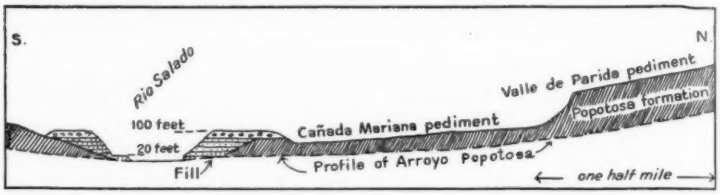


FIG. 11.—Cross section of Rio Salado along the Arroyo Popotosa

No fill is found to the west of the Box Canyon (T. 1 N., R. 2 W.); nor have any very extensive areas of alluvial fill been found along the Rio Puerco or the Rio Grande to the north of the mouth of the Rio Salado except in the vicinity of La Joya.

Along the east side of the Rio Grande from a little north of Contreras to a short distance south of La Joya there are remnants of a cut-and-fill terrace which merges eastward with gravel-capped remnants of the *Cañada* Mariana pediment. On Figure 2 this cut-and-fill terrace is not differentiated from the *Cañada* Mariana pediment. This fill apparently dates from a time when the Rio Grande followed a somewhat more easterly course than at present—from the vicinity of Contreras to La Joya. At a somewhat later time the Rio Grande swung westward and its eastern tributaries—notably the Aqua Torres and the Arroyo Cibola—aggraded their channels in respect to the new position of the main stream, a process originally described by C. R. Keyes.[32] Recently the Rio Grande again under-

[32] "Aggraded Terraces of the Rio Grande," *Amer. Jour. Sci.*, Vol. XXIV (4th ser., 1907), pp. 467–72.

cut its eastern bank and dissected the fill to give the present terrace. This process is aided by the recent upbuilding of the Rio Puerco fan caused by the incision of the Rio Puerco which began about 1885.[33] This eastward cutting of the Rio Grande forced the Middle Rio Grande Conservancy District to abandon its efforts for the protection of the irrigable land on the flood plain to the west of Contreras.

No well-developed river terraces are found along the Rio Grande or the Rio Puerco within the limits of the San Acacia area. As gravel terraces occur on the Rio Grande to the north, this lack of remnants must be due to severe lateral planation in this area.

ARROYO CUTTING

The Rio Puerco, the Rio Salado, and most of the larger arroyos of the region have steep-walled channels which are from 10 to 40 feet deep and from 50 feet to three-quarters of a mile wide. These arroyos are cut into either the late Tertiary basin sediments or recent unconsolidated alluvium. The Rio Salado at Santa Rita (T. 2 N., R. 4 W.) flows in a deep arroyo whose channel is rapidly encroaching upon and undermining the irrigated orchards of the local inhabitants. In 1882 the Salado had a channel 48.84 feet wide and banks from 3 to 10 feet high.[34] In 1918 the channel was 550 feet wide and from 10 to 20 feet deep. The local inhabitants told P. B. Moore that exceptional rains and floods in 1883 washed out a road and formed a new channel which has since been gradually widened and deepened. La Jenze Ranch is situated on a bluff 20–30 feet above La Jenze Creek. The creek flows in a steep-walled channel from 50 to 300 feet wide. In the 1880's the creek flowed close to the level of the ranch, and a considerable area was under irrigation as indicated by the remains of ditches. Some of the tributaries of the Rio Salado and of La Jenze Creek are graded to a point about 10 feet above the level of the master-stream and meet the latter in a steep fall, i.e., they are hanging tributaries formed by a recent downcutting of the main arroyo.

The causes of arroyo cutting and the resulting soil erosion involve

[33] Bryan, "Historic Evidence on Changes in Channel of Rio Puerco, a Tributary of the Rio Grande in New Mexico," *Jour. Geol.*, Vol. XXXVI (1928), pp. 265–82.

[34] Bryan, "Channel Erosion of the Rio Salado, Socorro County, New Mexico," *U.S. Geol. Surv. Bull. 790* (1926), pp. 17–19.

a combination of geologic, ecologic, and climatic factors which are the subject of much debate at the present time. Most writers attribute the incision to overgrazing.[35] Field studies by Bryan and by R. W. Bailey[36] have shown that the alluvium exposed by the recent incision contains unconformities and buried channels, giving evidence that arroyo cutting has not been restricted to the present period of land use. This fact suggests that overgrazing, although it may have caused the arroyo cutting at this particular time, is not the primary cause. Climatic changes appear to be a better explanation for the repeated cutting and filling of arroyos in the past.

ORIGIN OF PEDIMENTS

The San Acacia area, with a precipitation of from 10 to 20 inches a year, is only semiarid, and stream erosion is the most active and probably by far the most important process in the formation of the pediments. Although a detailed analysis of the origin of these pediments must await the time when adequate topographic maps will be available, it is possible to present some tentative conclusions regarding their formation.

The cap of caliche on the pediments, thickest on the older Tio Bartolo surface and thinner but, nevertheless, a resistant layer on top of the younger Valle de Parida and *Cañada* Mariana pediments, preserves these surfaces and leads to the formation of falls and rapids (nickpoints) along the dissecting streams. The *Cañada* de Mariana Chavez rises near Ladron Peak (Fig. 2) and flows northward across the Valle de Parida pediment, the *Cañada* Mariana pediment, and the present-day flood plains (a partial pediment) to join the Rio Puerco. There are several breaks in gradient (nickpoints) along the course of the *cañada:* one where its tributaries head in the small Tio Bartolo remnant to the north of Ladron Peak, another where the arroyo cuts down toward the level of the *Cañada* Mariana

[35] Bryan, "Date of Channel Trenching (Arroyo Cutting) in the Arid Southwest," *Science*, Vol. XXXV (1925), pp. 338–44; Cooperrider and Hendricks, *op. cit.*

[36] "Epicycles of Erosion in the Valleys of the Colorado Plateau Province," *Jour. Geol.*, Vol. XLIII (1935), pp. 337–55; Bryan, "Historic Evidence on Changes . . . . ," *op. cit.*, pp. 265–82.

pediment, a third where the *cañada* cuts down to the level of the present flood plains, and a fourth where the *cañada* empties into the present channel of the Rio Puerco.

The abundance of parallel drainage lines where a high pediment is being dissected to the level of a lower one attests to the dominance of stream action. These parallel streams are closely spaced. The actual number of long, narrow, parallel ridges and gulches in the areas to the north and east of Ladron Peak, near the Cerritos de Las Minas and between the Aqua Torres and the Arroyo Cibola, is far greater than the number actually shown on the limited scale of Figure 2. These parallel streams are reducing the higher pediment remnants down to that of the next lower one. They undercut their banks to some extent and tend to meander a little. However, they can cut sidewise only a few hundred yards to perhaps half a mile before encountering the neighboring gulch. Along the major arroyos the amount of lateral cutting is more than along the much more numerous small intervening arroyos. The Socorro quadrangle shows that some of the larger arroyos on the east side of the Rio Grande, such as Arroyo de Los Pinos and Arroyo de La Parida, have cut somewhat meandering channels and are engaged in developing a slightly wider flood plain.

The main reduction of a high pediment remnant down to that of a lower one is by the downward and headward cutting of many parallel or subparallel gulches. In the area to the north of Ladron Peak the Valle de Parida pediment is bordered on the northeast by remnants of the *Cañada* Mariana pediment. The topographic unconformity between the two surfaces trends in a northwesterly direction and is indented by several steep-sided parallel gulches which run northeastward at right angles to the main break in slope. These gulches are shown on Figure 2. Between them the scarp is indented by numerous smaller gulches from a few tens to hundreds of feet in length, too small to be shown on Figure 2. At the present time this northwest-trending escarpment or topographic unconformity is being driven back by the headward cutting of these numerous small gulches, and the present remnant of the *Cañada* Mariana pediment is being extended southwestward at the expense of the Valle de Parida pediment remnant. The breaks in gradient (nickpoints) along

the main arroyos at or near the lower (northeastern) edge of the *Cañada* Mariana pediment have not yet cut back to the lower edge of the Valle de Parida pediment. Therefore, the cutting-back (southwestward) of the inner edge of the *Cañada* Mariana pediment is going on in the same manner as it did when the Rio Puerco was flowing at the *Cañada* Mariana level or about 150 feet above its present channel. Post-*Cañada* Mariana dissection has as yet had no effect on the formation of the upper or southwestward portion of the *Cañada* Mariana pediment. It is concluded, therefore, that the *Cañada* Mariana pediment has been formed by the retreat of this scarp from the flood plain of the Rio Puerco, where it was formed by the incision of the Puerco because of the lowering of the master-stream—the Rio Grande—this retreat being caused by the headward cutting of many subparallel gulches in the manner of retreat of the scarp at present.

The parallel northeasterly tributaries of the *Cañada* de Mariana Chavez which indent the edge of the Valle de Parida pediment are not engaged in swinging laterally and cutting back the intervening ridges of the Valle de Parida remnants. These northeasterly gulches are narrow right to the edge of the main escarpment.

This process of the retreat of escarpments by the headward cutting of myriads of parallel gulches, the escarpments being formed by the downcutting of the main drainage lines, is responsible for the formation of the Valle de Parida and *Cañada* Mariana pediments and, in part, of the present flood plains. The caliche cap on the pediments has aided this process by forming breaks in gradient (nick-points) along the main streams. The unconsolidated basin deposits beneath the caliche cap are also removed by ground-water sapping from the base of the scarps, which process tends to accentuate the break in slope between two surfaces. It is doubtless true that the main arroyos such as the Rio Salado and the Arroyos Cibola and Abo have by lateral planation widened their flood plains to some extent during Valle de Parida and *Cañada* Mariana time.

Although it is probable that the Tio Bartolo pediment was formed by the same set of processes as cut the younger surfaces, yet near the high mountain masses lateral planation by streams emerging from the highlands may have operated to form rock fans in the manner

visualized by Johnson.[37] The small Tio Bartolo remnant to the north of Ladron Peak (Fig. 8) has a roughly fan-shaped form. As far as known this surface is cut across pre-Cambrian crystalline rocks and volcanic rocks of Tertiary age.[38] Its surface is mantled by a bouldery gravel, and its slope is much steeper than that elsewhere, probably as much as 250 feet to the mile. Somewhat similar fan-shaped surfaces are found on the western and eastern sides of the Sierra Ladron. All such surfaces are cut across either pre-Tertiary rocks or the Tertiary volcanics, whereas the lower pediments are cut almost without exception across the relatively soft and pervious Tertiary basin deposits.

CALICHE

The surface of many arid and semiarid regions is covered by a layer of lime hardpan or caliche.[39] Such a deposit is characteristic of the older and formerly more extensive erosion surfaces (Fig. 12) in the San Acacia area.[40] The alluvial cover of the younger erosion surfaces contains a considerable amount of calcium carbonate, although the cap is not cemented. A mantle of indurated caliche of varying thickness (the "old age" type of Price) overlies most of the remnants of the Tio Bartolo pediment to the west of Sierra Ladron and Silver Creek. At the North end of the mesa between La Jenze and Silver creeks about 50 feet of gravel caps the erosion surface and rests unconformably on deformed basin deposits (Santa Fe formation). The upper 19 feet of the pediment alluvium is caliche, and here the following section was measured.

The nodular caliche is composed of irregular, nodular masses as much as 8 inches in diameter with rudely concentric internal struc-

[37] D. W. Johnson, "Rock Fans of Arid Regions," *Amer. Jour. Sci.*, Vol. XXIII (1932), pp. 389–416.

[38] Denny, *op. cit.*, Fig. 1.

[39] J. F. Breazeale and H. V. Smith, "Caliche in Arizona," *Univ. of Ariz. Agric. Exper. Sta. Bull. 131* (1930), pp. 419–41; D. G. Runner, "Geology for Civil Engineers" (Chicago: Gillette Publishing Co., 1939), chap. xi; W. A. Price, "Reynosa Problem of South Texas, and Origin of Caliche," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XVII (1933), pp. 488–522, and discussion in *ibid.*, pp. 1277–81.

[40] Bryan and McCann, "The Ceja del Rio Puerco . . . . ," *op. cit.*, p. 5; W. C. Davidson, "Caliche and Other Native Road Materials," *New Mex. Highway Jour.*, July, 1925.

ture. These nodules are composed of calcium carbonate and of fine-grained detrital material in varying proportions. The massive caliche (Fig. 12) is a rock composed of fine sand and of almost pure, fine-grained calcite. These two types are closely interstratified as more or less horizontal bands or as irregular masses. Both types are intersected by long, narrow veins and irregular cavities, from several centimeters to less than 1 millimeter in length, which are lined with small calcite crystals.

FIG. 12.—Beds of banded and massive caliche resting unconformably on pre-Tertiary rocks (red shale, Mesozoic [?]) at western edge of Tio Bartolo pediment to west of Ladron Peak.

Under the microscope the fine-grained massive caliche consists of minute interlocking crystals of calcite, less than 0.01 millimeter in diameter, together with irregular masses of very fine-grained white material which could not be identified. The whole mass contains a considerable number of minute, gray-colored specks which are probably detrital particles of silt and clay. The coarser-grained phase consists of angular fragments of quartz, quartzite, plagioclase, and microcline, together with a few grains of biotite, hornblende(?), iron oxide, olivine(?), and probably several other minerals. The quartz and feldspar grains are clear. Some of the former show strain shad-

ows, as do those in the fragments of quartzite. Many of the plagioclase crystals are zoned. Some of the grains of iron oxide and of the dark minerals have altered slightly to limonite. All grains are angular except for one or two of the larger ones which show a somewhat rounded form. The grains of quartz, quartzite, and microcline come from the pre-Cambrian crystalline rocks, whereas the zoned feldspars resemble those found in the Tertiary volcanics. The thin sections show numerous narrow veins or cavities, from 0.05 to 0.30 millimeter in width, which are partially or completely filled by interlocking calcite crystals. There are also numerous small, irregular cavities.

TABLE 1

SECTION OF CALICHE EXPOSED AT NORTH END OF MESA BETWEEN LA JENZE AND SILVER CREEKS

	Feet
Nodular caliche	3
Massive caliche	2
Nodular caliche	2
Massive caliche, light gray to white, sandy; imperfect stratification, beds 2–5 feet thick; slightly undulating contact at base; rests on gravel and sand	12
Total thickness	19

At other localities the caliche contains sand and gravel in varying amounts and forms the cement between the detrital grains. Some beds of caliche contain lenses of large calcite crystals which are arranged in bands, apparently representing successive periods of deposition in open cavities which were several inches in width.

The caliche is undergoing solution at present. Its upper surface is very rough and is etched into solution pits ("tinajitas") which are more than an inch deep and several feet in diameter (Fig. 13). Such a process is the rule in this climate for all fragments of calcareous rocks lying undisturbed on the surface for a considerable period of time.[41] Solution facets and solution furrows, of the types described

[41] Bryan, "Solution-faceted Limestone Pebbles," *Amer. Jour. Sci.*, Vol. XVIII (5th ser., 1929), pp. 193–208; J. F. Smith, Jr., and C. C. Albritton, Jr., "Solution Effects on Limestone as a Function of Slope," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 61–78.

by Smith and Albritton, are also present on caliche and on limestone. Solution of the caliche is also going on along more or less vertical joints (Fig. 13) which intersect the beds of massive caliche. Redeposition takes place at lower levels. The nodular caliche at the surface may be the result of present-day solution as suggested by Price.[42]

In the San Acacia area the thickest deposits of caliche form a part of the alluvium which caps the remnants of the Tio Bartolo pediment to the west and south of the Sierra Ladron (Fig. 12). The

FIG. 13.—Jointed and pitted surface of caliche which caps Tio Bartolo pediment to west of Ladron Peak. Photograph by C. E. Stearns.

caliche is the result of processes active when ephemeral streams were cutting this erosion surface and transporting across it the sand and gravel which are now so intimately associated with the caliche. The thin bands of caliche, which consist of relatively pure calcium carbonate with only a small amount of detrital material, may represent either deposition in small pools in stream channels or an accumulation of lime in the *B* horizon of the soil developed during the cutting of the pediment, the *A* horizon having been removed by subsequent erosion. The beds of massive caliche are probably the result of the deposition of calcium carbonate in the subsoil caused by evaporation of ground water at the surface.

[42] *Op. cit.*, p. 501.

The author is in general agreement with the idea that thick deposits of caliche are the result of long-continued soil formation under an arid climate.[43] However, the great thickness of the caliche on the Tio Bartolo pediment remnants to the west and southwest of the Sierra Ladron, as compared with that on the older and originally more extensive Ortiz pediment in adjoining sections of the Rio Grande Valley, demands some special explanation. Near Abeytas the caliche cap on the Ortiz(?) surface consists of from 10 to 20 feet of soft nodular caliche and caliche-bearing sand (Fig. 9). Near Albuquerque the Ortiz surface (Llano de Albuquerque) has a 2–20-foot covering of caliche.[44] Furthermore, the remnants of the Tio Bartolo pediment to the east of Sierra Ladron have only a thin covering of soft, gravelly caliche from 1 to 5 feet thick. These remnants were cut by streams which headed in the pre-Cambrian crystalline rocks of the Sierra Ladron.

The excessive thickness of caliche to the west of the Sierra Ladron is thought to be due to the high lime content of the ground water in that region caused by its proximity to the outcrops of limestone on the west side of the Ladron. During Tio Bartolo time evaporation at the surface would cause the water to rise by capillary action into the subsoil and deposit these unusually thick layers of massive caliche. It has been argued that once a foot or two of hardpan is formed in the subsoil it will seal off the ground water below and prevent continued evaporation and deposition. However, the massive caliche of this area is porous and contains an abundance of cavities which do not appear to be the result of recent solution and which should have permitted the capillary rise of ground water.

SAND DUNES

A dune belt is located on the north side of the Rio Salado near its mouth. The trend of the belt is northwesterly (Fig. 14), but the individual dunes which are not over 40 feet high trend northeasterly. The sand is derived from the channel of the Rio Salado and carried

[43] *Ibid.;* Bryan and McCann, "The Ceja del Rio Puerco . . . . ," *op. cit.;* W. G. Woolnough, "Origin of White Clays and Bauxite, and Chemical Criteria of Peneplanation," *Econ. Geol.*, Vol. XXIII (1928), pp. 887–94.

[44] Bryan and McCann, "The Ceja del Rio Puerco . . . . ," *op. cit.*, p. 5.

up the north bank of the arroyo by southwesterly winds. At one locality on the north bank of the Rio Salado a gulch descends to the level of the arroyo. The lower end of the gulch is filled with a ridge of sand which is advancing up the gulch (northward). Small dunes are present along many arroyos where sandstorms have been frequently observed during July and August. These dunes are probably in part of very recent origin and have been formed as the result of

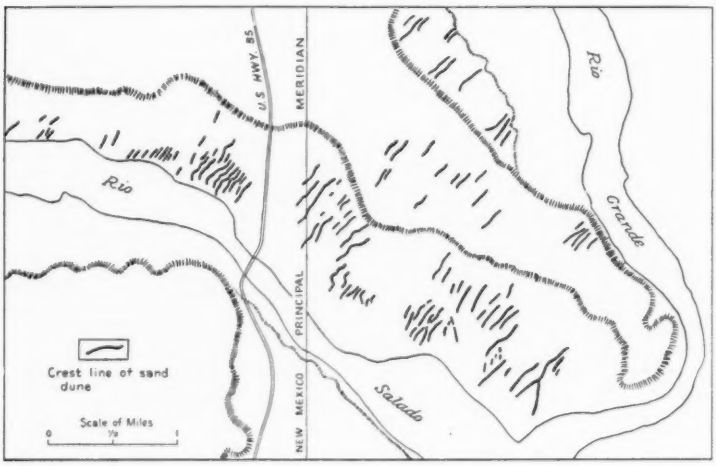


FIG. 14.—Sand dunes, Rio Salado

recent channel trenching (arroyo cutting) which has made available a great abundance of sand.

Areas of sand, now largely covered by vegetation, lie on the east side of La Jenze Creek to the south of La Jenze Ranch and also to the north of the creek near the eastern edge of the Bear Mountains. It is probable that these dune areas were formed at a time previous to the present.

VENTIFACTS

Pebbles and boulders polished by sandblasting are found near some of the dunes. Ventifacts are reported by C. E. Needham[45] from the south end of the Valle del Ojo de La Parida.

[45] "Ventifacts from New Mexico," *Jour. Sed. Petrology*, Vol. VII (1937), pp. 31–33.

On the east side of the Rio Grande, about 2 miles to the west of Turututu Butte, there is a low hill (shown as a residual above Tio Bartolo surface on Fig. 2; T. 2 N., R. 2 E.) composed of vesicular basalt. Large boulders lie on the surface surrounded by scattered masses of coarse sand overgrown by grass (Fig. 15). The surfaces of these boulders have been etched by sandblasting (Fig. 16). Grooves more than an inch deep are localized by the vesicles in the lava. The flutes trend north 80° west to south 80° west. The ventifacts are

FIG. 15.—Sandblasted boulders of vesicular basalt. Top of low basalt hill located 2 miles west of Turututu Butte.

most abundant on the east side of the hill and are absent on its western side. The abrading winds, therefore, came from the east and were strong enough to carry sand over the top of the low hill to a height of at least 4 feet above the ground. The wind-cut surfaces are weathered and dull. Some of the larger boulders have been fractured and broken to pieces since wind work occurred. The smaller boulders, obviously the product of relatively recent weathering, do not show evidence of abrasion. Thus the wind abrasion is ancient and took place when easterly winds of considerable velocity rather than the present southwesterly winds prevailed.

Similar wind-cut boulders are found on top of a butte of volcanic rock which lies about 4 miles east-southeast of Contreras.[46] This

[46] Denny, *op. cit.*, Fig. 1.

wind abrasion is not modern and records sandblasting of similar intensity produced by winds of easterly direction. The butte rises above the level of the neighboring remnants of the Tio Bartolo pediment (Fig. 2; T. 2 N., R. 2 E.), and its summit is at least 50 feet above the arroyo to the east, which separates the basalt butte from a somewhat larger residual farther eastward. When wind abrasion oc-

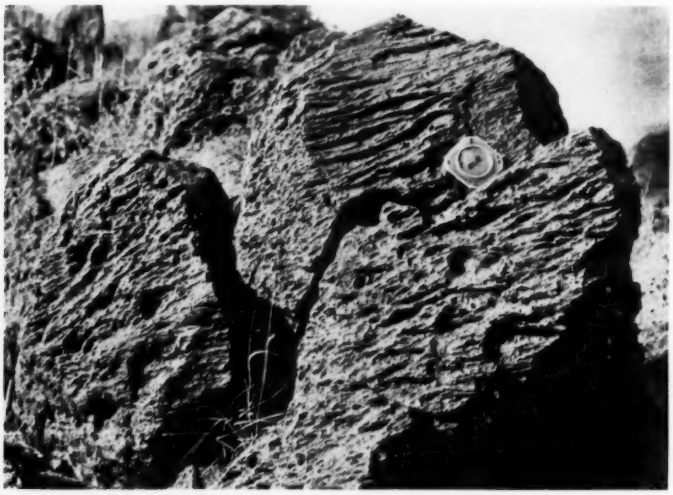


FIG. 16.—Sandblasted grooves in vesicular basalt. Locality same as Fig. 15

curred, the Tio Bartolo pediment must have extended across the present gulch to join the remnants near the basalt butte, otherwise easterly winds would have had to carry the abrading sand up vertically more than 50 feet from the bottom of the arroyo to the top of the butte.

It is certain that this wind work took place long ago, although whether the date is late Pleistocene or Recent is unknown. Bryan and Albritton[47] record the presence of wind-polished rocks in Trans-Pecos Texas and tentatively relate the period when they were formed to the post-Neville–pre-Calamity interval of erosion in the

[47] "Wind-polished Rocks in Trans-Pecos Texas" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 1902.

Davis Mountains. Easterly winds in the San Acacia area during late Quaternary time do not fit into any readily conceived meteorological system, nor are they compatible with the wind direction inferred by F. A. Melton in the Great Plains 250 miles to the east of this locality.[48]

RÉSUMÉ OF QUATERNARY HISTORY

The deformation which closed the deposition of the Santa Fe formation in late Pliocene or earliest Pleistocene time was followed by a long period of erosion during which the Rio Grande was established as the master-stream. The period culminated in the development of a widespread erosion surface—called the "Ortiz"—which was graded to the Rio Grande at an altitude of about 400 feet above its present flood plain. The Rio Puerco was probably not in existence at this time. There is some evidence of deformation near the close of Ortiz time, and this may have been important as an aid to piracy in establishing the Rio Puerco in its present course.

This period was, however, ended when the Rio Grande lowered its channel about 150 feet and established a new gradient about 250 feet above the present flood plain. The tributaries lowered their valleys in accord with the new position of the master-stream, and a second widespread erosion surface—the Tio Bartolo—was formed. In the San Acacia area the Ortiz surface was almost entirely destroyed during Tio Bartolo time. At this stage the Rio Salado probably followed a southeasterly course from Santa Rita across the Snake Ranch Flats to Socorro. Near the close of Tio Bartolo time (perhaps in post–Tio Bartolo time) movement took place along a fault to the east of the Magdalena Mountains by which the Snake Ranch Flats were depressed relative to the mountain block to form the present scarp (Fig. 2; T. 1 and 2 S., R. 3 W.).

At the close of Tio Bartolo time the Rio Grande once again lowered its bed until it reached a grade only 150 feet above the present flood plain. There it was stabilized for a time during which the Valle de Parida pediment was formed. During this interval a westward tributary of the Rio Grande cut headward through the Sierra

[48] "A Tentative Classification of Sand Dunes—Its Application to Dune History in the Southern High Plains," *Jour. Geol.*, Vol. XLVIII (1940), pp. 113–74.

Ladron–Socorro Mountains axis and committed piracy on the ancestral Rio Salado to form the present-day stream.

Next, in what was probably late Pleistocene time, the Rio Grande cut down another 100 feet to a level only about 50 feet above the present flood plain. With the master-stream stabilized at this grade, the tributaries formed another pediment—the *Cañada* Mariana.

The cause for these repeated periods of downcutting by the Rio Grande is unknown but seems certainly to be due to changes which originated far downstream. At about this time the Rio Salado, in the section which lies to the east of the Box Canyon, cut down its channel to about the present level and then filled it up to a point about 100 feet above its present grade. The cut-and-fill terraces found in the Socorro quadrangle may have been formed at this same time. It is uncertain whether or not the *Cañada* Mariana pediment was completed before or after this period of filling.

In very late Pleistocene or Recent time the Rio Grande has cut down its bed to the grade of the present flood plain, and its tributaries have done likewise. Since 1885 most of the tributaries of the Rio Grande have incised their beds in steep-walled canyons, and an epoch of rapid dissection is in progress. This dissection causes silt to be deposited on the Rio Grande flood plain.

ACKNOWLEDGMENTS.—Dr. Kirk Bryan, of Harvard University, gave abundantly of his time and energy both during the field work and in the preparation of the manuscript. During 1935 the writer was ably assisted in the field by A. H. Smith, R. S. Folsom, and D. Rose; in 1936 by R. S. Folsom and K. M. Clark, Jr.; and in 1937 by C. E. Stearns. The Middle Rio Grande Conservancy District and Mr. Stanley Phillipi furnished maps and loaned a tripod. It is a pleasure to acknowledge the hospitality and many courtesies extended by residents of the area, especially Messrs. F. G. Fisher, H. E. Byers, and G. A. Eckerson, of Belen, Mr. R. Lloyd, of Abeytas, and Mr. R. H. Perry, of Magdalena.

STRATIGRAPHY AND PALEONTOLOGY OF A NEW MIDDLE AND UPPER PLIOCENE FORMATION OF SOUTH-CENTRAL KANSAS[1]

JOHN C. FRYE
United States Geological Survey, Lawrence, Kansas

CLAUDE W. HIBBARD
University of Kansas

ABSTRACT

The stratigraphy of the Emma Creek formation, a newly differentiated Middle and Upper Pliocene formation of south-central Kansas, is described. The lithology of the formation and its origin, source areas, and physiographic history are discussed.

The vertebrate fossils of this formation, the younger McPherson formation (restricted), and the early controversy over the dating of the "McPherson Equus Beds" are discussed.

INTRODUCTION

An investigation of the geology and ground-water resources of the "Equus Beds" area was undertaken in 1937 by the United States Geological Survey in co-operation with the Kansas State Geological Survey and the Kansas State Board of Health, and later also with the city of Wichita. This work was under the immediate supervision of S. W. Lohman, geologist in charge of ground-water investigations in Kansas, and a summary of the results was published in 1940.[2] During the course of this investigation it was found that, although there existed an extensive body of literature dealing with the Paleozoic and, to a lesser extent, with the Mesozoic rocks of southern Kansas, the Tertiary and Quaternary geology of the region had received but slight notice since the early work of the Kansas Geological Survey. As the important fresh-water-bearing horizons occur entirely within the Tertiary and Quaternary deposits, it was deemed advisable to map the surface extent of these beds and to augment

[1] Published with the permission of the director of the Geological Survey, U.S. Department of the Interior, and the director of the Kansas State Geological Survey.

[2] S. W. Lohman and John C. Frye, "Geology and Ground-Water Resources of the 'Equus Beds' Area of South-Central Kansas," *Econ. Geol.*, Vol. XXXV (1940), pp. 839–66.

the early geologic reconnaissance by more detailed study. The geology was mapped by J. C. Frye, and the map published in 1940.[3] Vertebrate fossils collected during this field work were sent to Claude W. Hibbard for identification. In the present paper the stratigraphy and lithology are discussed by J. C. Frye, and the vertebrate fauna and its age are discussed by Claude W. Hibbard.

The field data on which the following discussion is based were obtained during the summer and fall of 1938 and the spring of 1939. Surface work was supplemented by studies of well logs supplied by the water-well drillers operating in this area, depths to bedrock from drill holes put down by several oil companies, sample-study logs of cable-tool test holes drilled by the city of Wichita under the direction of the Federal Geological Survey, and by logs and samples from rotary test holes and wells drilled in the area by the state and federal geological surveys and by the city of Wichita, both for exploratory purposes and for public-supply wells.

The area studied comprises the so-called "Equus Beds" area of south-central Kansas. It embraces approximately 1,300 square miles, extending from the Arkansas River northward to the Smoky Hill River and from Newton westward to within a few miles of Hutchinson. The location of the area is shown in Figure 1.

The bedrock floor underlying the Tertiary and Quaternary deposits in this area is composed of Permian and Cretaceous rocks. The Permian Wellington formation, which crops out along the eastern border of the area, and the Permian Ninnescah shale, which crops out in the northwestern part, have recently been described by George Norton.[4] Shales and sandstones of Cretaceous age which occur in the northeastern part of the area have been described by W. H. Twenhofel.[5] The regional dip of the Permian beds is to the north-northwest; and the dip of the Cretaceous rocks, which unconformably overlie the Permian, is nearly flat. This bedrock floor is composed largely of shale but contains some sandstone, limestone, and

[3] Lohman and Frye, *ibid.*, p. 843.

[4] "Permian Redbeds of Kansas," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIII (1939), pp. 1758–74.

[5] "Geology and Invertebrate Paleontology of the Comanchean and 'Dakota' Formations of Kansas," *Kan. Geol. Surv. Bull. 9* (1924), pp. 30–34.

gypsum. The Hutchinson salt beds of the Wellington formation occur in the western part of the area at a depth of only a few hundred feet below the surface of the bedrock floor. Solution of this salt appears to have played an important role in the late Cenozoic development of the region.

STRATIGRAPHY

In 1897 Erasmus Haworth and J. W. Beede[6] described and mapped the extent of a series of deposits in this area which they referred to the Pleistocene and named the "McPherson Equus Beds."

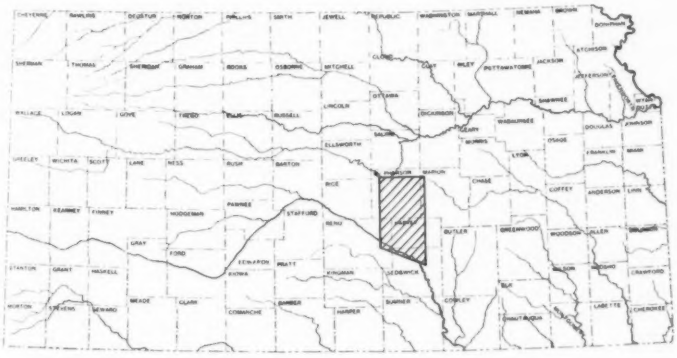


FIG. 1.—Map of Kansas showing the location of the area studied

They included in this formation all of the surficial deposits in the area here under consideration. On the geologic maps of Kansas[7] issued in 1937 a large part of the sand-dune area and the alluvium along the Arkansas River were distinguished from the McPherson formation, or "Equus Beds," but the original mapping in the northern part of the area was accepted with little or no change. During the course of the field work in the area by J. C. Frye it became apparent that the so-called "Equus Beds," instead of being a stratigraphic unit, comprise five divisions distinguishable both lithologically and physiographically. These divisions comprise a high-level Tertiary formation, a Pleistocene outwash formation, Pleistocene

[6] "The McPherson Equus Beds," *Kan. Univ. Geol. Surv.*, Vol. II (1897), pp. 287–96.

[7] Geologic Map of Kansas (Kansas Geol. Survey, 1937).

and Recent alluvium, a thick loess deposit of Pleistocene age, and Pleistocene and Recent dune sand. Claude W. Hibbard has examined fossils collected during the present investigation and by previous workers and assigns the oldest of these five subdivisions to the Middle and Upper Pliocene and the others to the Pleistocene and Recent.

In 1940 Lohman and Frye[8] named the Pliocene portion of these deposits the Emma Creek formation and restricted the McPherson formation to include only the Pleistocene deposits of fluvial origin. Although these formations were described briefly in that paper, it is believed that a more complete description of these Pliocene deposits is desirable, particularly with reference to their contained vertebrate fossils.

EMMA CREEK FORMATION

CHARACTER AND SUBDIVISIONS

The Emma Creek formation is composed of interbedded clay, silt, sand, and gravel, poorly sorted and, in general, containing an abundance of lime nodules. Several distinct lithologic types are described in some detail in order to give an adequate understanding of the formation. However, they are not considered members or named, owing to the inadequacy of the exposures and the extremely lenticular nature of the deposits.

A clay of quite variable thickness locally occurs near the base of the formation. This clay is dominantly gray in color but locally shows mottling and banding of brick red. It is usually a tight, blocky clay, but it may contain an admixture of sand and in places grades into loose sand. This material appears to have accumulated under slack-water conditions and may be either a lacustrine or a flood-plain deposit. The clay and sand underlies, at least in part, the sand-dune areas east of Hutchinson and east of Halstead. A good exposure of the blocky-clay phase occurs along the bank of West Emma Creek in the NW. $\frac{1}{4}$, Sec. 27, T. 20 S., R. 1 W.

Another prominent type, which locally overlies the gray clay, consists of a red-brown sandy silt that resembles loess on the exposed surfaces and is quite hard when dry. In most places this material contains nodules of calcium carbonate that range in diameter from

[8] *Op. cit.*, p. 849.

a few millimeters to a foot and are generally soft and chalky; in some places exposures are colored ash gray by a surface wash of calcareous matter. This phase is best exposed for several miles north of Wichita, 1–2 miles east of U.S. Highway 81. It also occurs in road cuts and creek banks along the headwaters of West and Middle Emma creeks. Owing to the general absence of bedding, the small percentage of coarse material, and fragments of plant remains, this appears to be a flood-plain deposit and so is referred to as the "flood-plain phase."

In the area south of Canton the material that comprises the uppermost part of the formation is a coarse, red-brown, quartz sand. Locally, this sand is well sorted; but elsewhere it contains cobbles of shale, Dakota sandstone, and large nodules of calcium carbonate. In one locality thin zones have been tightly cemented with iron oxide, and the intervening loose sand is tan to dirty gray in color. Locally, lenses of sand have been indurated by calcium carbonate to a friable gray sandstone. The thickness of this phase in the Canton area is not known with certainty; it probably does not exceed 20–30 feet southeast of Canton. In the northwestern part of the area this phase occurs as a fairly coarse gravel. The pebbles are mostly of Dakota sandstone. This sand and gravel are found capping the hilltops, unconformably overlying the Permian shales, and in some places are overlain by loess. This phase is best exposed in two gravel pits located respectively 2 miles northwest of Johnstown and $4\frac{1}{2}$ miles south of Marquette; in both pits the gravel is quite coarse and cross-bedded. The pit south of Marquette is shown in Figure 2. Here the sand and gravel reach a thickness of somewhat more than 40 feet and overlie the Ninnescah shale of Permian age. However, this phase decreases in thickness southward.

At a few places in the southern part of the area a cemented conglomerate, or "Mortar bed," occurs at or near the base of the Emma Creek formation and is overlain by red-brown sandy silt or brown sand. This "Mortar bed" contains not only pebbles of Dakota rocks but also pebbles of granite. This material is well exposed along the road cut and quarry in the NE. $\frac{1}{4}$, Sec. 21, T. 26 S., R. 1 E., as shown in Figure 3. At this locality these beds have been assigned by

Norman Plummer[9] to the Ogallala formation. This and several similar exposures to the east of this area have been discussed by Louis Michaelson,[10] who reached no definite conclusion as to their age or source.

PETROLOGY

In an attempt to determine the source of these deposits attention was given to the petrologic types represented in the sands and gravels of the Emma Creek formation, the younger McPherson formation (restricted), and the alluvium of the Arkansas River. In their discussion of the mineralogy of the McPherson sands, Haworth and Beede[11] state that they are notably free from feldspars and appear to have been derived mainly from rocks of the Dakota group. Although they do not state the locality from which these samples were collected, it is the opinion of the writer that they must have been taken from deposits now designated as the Emma Creek formation.

FIG. 2.—Pit in the gravel or channel phase of the Emma Creek formation. SW. $\frac{1}{2}$, SE. $\frac{1}{4}$, Sec. 12, T. 18 S., R. 5 W.

[9] "Rock Wool Resources of Kansas," *Kan. Geol. Surv., Mineral Resources Circ.*, Vol. XXXVIII, No. 5 (1937), pp. 50–51.

[10] "Terrace Sands of Eastern Sedgwick County, Kansas," *Trans. Kan. Acad. Sci.*, Vol. XLI (1938), pp. 213–17.

[11] *Op. cit.*

The Emma Creek sand and gravel (except for the "Mortar-bed" material and a few thin zones related to that material) are notably lacking in feldspar and other Rocky Mountain rock types, although rarely occasional grains can be found even in this material. The sands consist principally of quartz, and the gravels contain pebbles of chert, re-worked concretions, harder phases of Dakota sandstone, and rounded fragments of shale. These types all indicate a source

FIG. 3.—"Mortar bed" phase of the Emma Creek formation. This Ogallala-like material is here unconformably overlain by red-brown unconsolidated sandy silt and overlies shales of the Wellington formation.

from the area of outcrop of the Permian and Cretaceous rocks to the east and north of this area. The "Mortar-beds" phase, and related beds, on the other hand, contain a considerable percentage of granite pebbles and other western rock types.

In contrast to the Emma Creek formation, the alluvium of the Arkansas River consists dominantly of Rocky Mountain rock types. The gravels invariably contain abundant pebbles of granite, pegmatite, and other igneous-rock types, in addition to material that appears to have been derived from the Tertiary rocks of the Western Plains. Furthermore, the sands of the McPherson formation (restricted), although containing abundant quartz, also contain grains

of feldspar and of other igneous rocks and grains of pink and red quartzite similar to that which occurs typically as erratics in the glaciated area of northeastern Kansas.

GEOLOGIC HISTORY

With the possible exception of the basal clay the Emma Creek strata all appear to be fluvial deposits of both channel and flood-plain type. It is difficult, however, to locate the positions and trends of the axial streams that controlled their deposition. The regional slope on the top of the Emma Creek deposits in the area south of Canton is from 6 to 8 feet per mile in a southwesterly direction. If this surface is projected so as to cross the north-south trough located just west of McPherson, which contains the thickest deposits of the McPherson formation (restricted), the slope of the whole region is increased slightly, and its descent trends nearly due south. The slope of the bedrock floor in the northeastern part of the area is only a few feet to the mile. It declines in a west-southwest direction. It thus appears that the major streams flowed toward the south or southwest.

The relation of the Emma Creek formation to the bedrock floor and to the younger McPherson formation and the overlying loess is shown in Figures 4 and 5. These cross sections are based primarily on logs and samples obtained from rotary test holes put down by the Kansas Geological Survey in co-operation with the Federal Geological Survey.

The Wellington formation underlies the entire area in question and dips to the west-northwest.[12] Although it cannot be established that the Hutchinson salt beds were exposed at the surface during the Tertiary, it is probable that formerly parts of them were closer to the surface than any remaining salt and likewise closer to vigorous ground-water circulation. Probably the most favorable period for solution in this horizon occurred at the time the Tertiary streams were deepening their channels prior to the deposition of the Ogallala and Emma Creek formations. Solution of this salt probably caused a depressional area along a line through McPherson and Halstead

[12] Norton, *op. cit.*

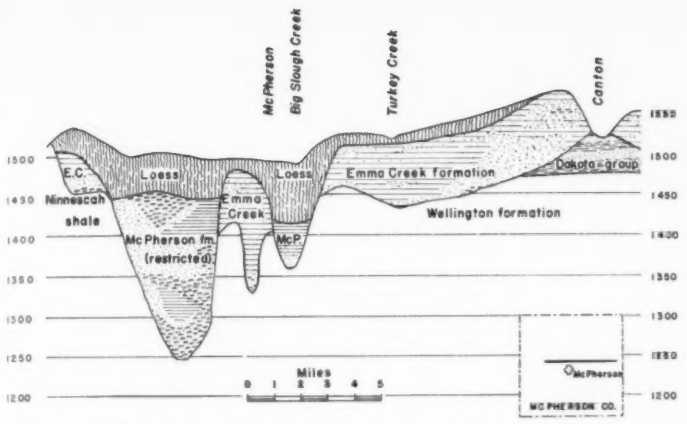


FIG. 4.—West-to-east section across the "Equus Beds" area, 1 mile north of McPherson, McPherson County, Kansas.

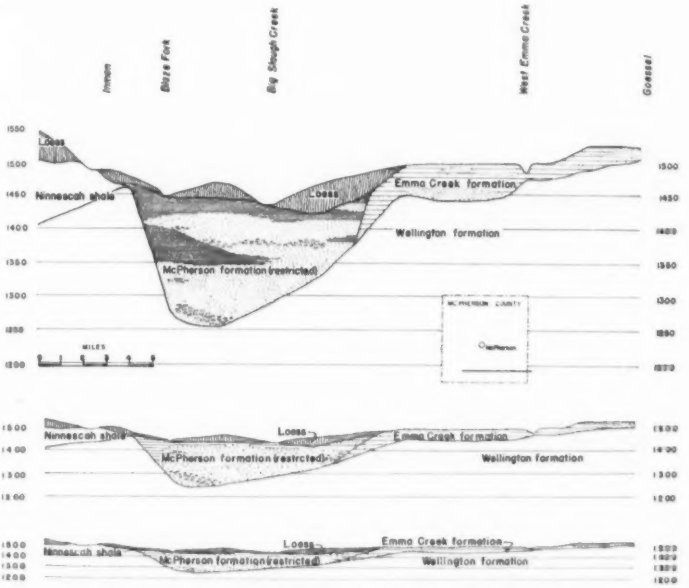


FIG. 5.—West-to-east section across the "Equus Beds" area, from Inman to Goessel, McPherson County, Kansas. This section is drawn to three different vertical scales in an attempt to show both the detail of the deposits and a more accurate representation of the slopes and unconformities involved.

and appears to have controlled the location of an axial stream in this area. Later ponded conditions may have existed, and streams from the west may have flowed into this body of slack water. These streams were depositing the coarser phases of the Ogallala formation nearer to the Rocky Mountains, and here they dropped the load of silt and clay that had been transported to this greater distance. Streams entering this area from the north and northeast also contributed to the deposition and, judging from the predominance of quartz grains in the coarser beds, probably supplied much of the sandy part of the basal gray clay and sand phase.

Probably this ponded area soon became filled with these sediments, and the streams may then have flowed on the surface of a depositional plain. It seems certain that deposition here during early Emma Creek time was alternately controlled by streams from the north and northeast and by streams from the west, and the deposits from the two sources interfinger. An exposure in the southern part of the area indicating interfingering of Pliocene deposits from the west and from the north is shown in Figure 6. Material from the Rocky Mountain area is lacking entirely toward the top of the formation and toward the northern part of the area. Additional evidence that the major streams that deposited the Emma Creek sediments came from the north and northeast lies in the fact that the sand and gravel, or channel phase, is more prominently developed and occurs at higher altitudes in the northern part of the area than in the southern part.

RELATION TO YOUNGER FORMATIONS

The Emma Creek formation is unconformably overlain at different localities in the area by the McPherson formation and by loess and dune sand of Pleistocene and Recent age. The relation of the Emma Creek formation to these younger formations is shown in Figures 3 and 4 and has been briefly described in an earlier publication.[13] As pointed out earlier, the sands of the McPherson formation contain materials derived from the Permian and Cretaceous rocks to the north and east in addition to igneous and metamorphic rock types from more distant sources. The presence of pink and red

[13] Lohman and Frye, *op. cit.*

quartzite, which occurs elsewhere in Kansas only in the glaciated area to the northeast, the predominance of well-sorted, cross-bedded sand, the topographic position, and presence of Pleistocene fossils, all indicate that these beds are outwash, or valley-train material, deposited by melt-water during the retreat of the major glacier in northeastern Kansas. Tributary valleys to the major outwash stream were blocked at the time of maximum fill in the McPherson Valley and were filled with locally derived sands and silts.

FIG. 6.—Exposure of the Emma Creek formation 100 yards north of county road, S.W. ¼, Sec. 9, T. 23 S., R. 1 W. Shows interbedding of flood-plain deposits of northern source, overlain by heterogeneous gray sandy clay from a western source, in turn overlain by sandy silt of typical northern Emma Creek type. The Emma Creek formation is here unconformably overlain by thin-bedded volcanic ash and terrace deposits.

Dune sand and loess overlie not only the Emma Creek formation but also the McPherson formation. The McPherson formation along its southern border merges laterally with the alluvium of the Arkansas River. Although these deposits are mainly Pleistocene in age, they are in part Recent.

AGE AND VERTEBRATE FOSSILS

The exact date when the first vertebrate remains were collected in McPherson County is unknown; but prior to 1889, J. A. Udden, pro-

fessor of zoölogy, Bethany College, sent to J. Lindahl, Springfield, Illinois, a sloth skull for study and identification. At the same time or earlier he sent the associated horse teeth and invertebrates to E. D. Cope for identification. Cope[14] in his paper illustrates the McPherson sloth skull and says of it: "Another species has been only found in the Ticholeptus formation of Kansas." Lindahl[15] in his paper quotes a letter dated December 10, 1890, from Professor Udden, which states that "Cope on the basis of the teeth of *Equus major* found in the same gravel deposit as the sloth, determined the age of the formation as belonging to the Equus beds." Lindahl adds a short postscript to his paper in which he corrects for Cope his error in referring the sloth skull from McPherson County to the Ticholeptus formation of Kansas, whereas it should have been attributed to the Equus beds. Lindahl was the first to apply the term "Equus beds" to the McPherson region on the basis of Cope's identification of the associated horse material.

J. A. Udden[16] questions the exact age of the McPherson deposits. He gives a detailed description of the deposit as observed, lists the fauna found with the sloth skull, and makes the following statement, based on the authority of Cope: "The fauna of the 'Equus beds' and that of the 'Megalonyx beds' must have been, at least to some extent, contemporaneous." Cope[17] gives a good discussion of his "Megalonyx fauna" and "Equus fauna." He regarded the McPherson fauna as *Megalonyx*, though in all probability as contemporary with the "Equus fauna" because of the presence of *Equus major*. Haworth and Beede[18] definitely assign the McPherson deposits to the Equus Beds; since that time the original workers have considered without question that all fossils from the McPherson area are derived from the McPherson Equus beds and are Pleistocene in

[14] "The Edentata of North America," *Amer. Naturalist*, Vol. XXIII (1889), pp. 657–64.

[15] "Description of a Skull of *Megalonyx leidyi*, n. sp.," *Trans. Amer. Phil. Soc.*, Vol. XVII (1892), pp. 1–10.

[16] "Megalonyx Beds in Kansas," *Amer. Geol.*, Vol. VII, No. 6 (1891), pp. 340–45.

[17] "The Antiquity of Man in North America," *Amer. Naturalist*, Vol. XXIX (1895), p. 596.

[18] *Op. cit.*

age, with the exception of a few who adopted W. B. Scott's[19] Sheridan beds and used the term "Sheridan beds" synonymously with "Equus beds."

The early writings of Cope and S. W. Williston on the fauna of the Equus beds of the plains region greatly influenced the later workers in this region to consider the McPherson deposits as strictly Pleistocene in age. Cope[20] says: "The Equus beds are always to be distinguished by the presence of *Elephas primigenius*, when other forms less easily perceived are not recognized." This statement was often quoted by Williston[21] in his papers on the Pleistocene faunas of Kansas. In the early study of the Equus beds all elephant remains were considered to be *Elephas primigenius*, as pointed out by O. P. Hay.[22] Therefore, the abundance of fragmentary elephant material found scattered on the surface of the deposits throughout the area by previous workers was considered to indicate Pleistocene deposits belonging to the Equus beds.

McPHERSON FORMATION (RESTRICTED)

Following is a list of all the known species from the McPherson formation (restricted); it is compiled from all previous publications on the fauna. As far as possible, all localities have been checked in the field.

Megalonyx leidyi Lindahl.—The type, a good skull taken from the base of a gravel pit near the southwest corner of Harper Township. Reported by Cope,[23] Lindahl,[24] Williston,[25] H. F. Osborn,[26] E. O. Deere,[27] and Hay.[28]

[19] *Introduction to Geology* (New York: Macmillan Co., 1897), pp. 532–33.

[20] "A Preliminary Report of the Vertebrate Paleontology of the Llano Estacado," *Tex. Geol. Surv., 4th Ann. Rept.* (1893), p. 75.

[21] "The Pleistocene of Kansas," *Kan. Univ. Geol. Surv.*, Vol. II (1897), pp. 299–308.

[22] "The Pleistocene of the Middle Region of North America and Its Vertebrated Animals," *Carnegie Inst. Wash. Publ.*, No. 322A (1924), p. 48.

[23] "The Edentata of North America," *op. cit.*, pp. 657–64.

[24] *Op. cit.*

[25] *Op. cit.*, p 304; "The Pleistocene of Kansas," *Trans. Kan. Acad. Sci.*, Vol. XV (1898), p. 93.

[26] *Age of Mammals* (New York: Macmillan Co., 1910), p. 461.

[27] "A Fossil Tusk Found in the Equus Beds in McPherson County," *Trans. Kan. Acad. Sci.*, Vol. XXI, Part I (1908), p. 117.

[28] *Op. cit.*

Mylodon cf. *harlani* Owen.—Reported by H. H. Nininger.[29] The specimen was a caudal vertebra taken December 29, 1924, by H. F. Hammann, from a gravel pit 12 miles northwest of McPherson. This is in the approximate area in which *Megalonyx leidyi* was found.

Smilodon sp.—Reported by H. J. Harnly,[30] taken from a sand pit on the Hammann farm northwest of McPherson. This specimen is a well-preserved brain case lacking the anterior part of the skull.

Mastodon americanus(?).—Reported by Nininger,[31] based upon a milk tooth with the crown nearly broken away. It was found 1 mile south of the town of McPherson. Its identity should be questioned, owing to the fragmentary condition of this tooth, the unknown depth from which it was taken, and its indefinite location from an area including deposits of both the Emma Creek formation and the McPherson formation. It seems very probable that it may represent the tooth of an earlier form.

The fragmentary tusk reported by Deere[32] taken at the north end of the W. $\frac{1}{2}$, Sec. 6, in Jackson Township, in all probability represents *Parelephas* instead of *Mastodon*, since elephant remains are abundant in that area and, to date, there is no authentic evidence that *Mastodon* material has been found in the deposits.

Elephas boreus Hay.—reported by Nininger[33] as *Elephas primigenius*. Most of the elephant remains from the plains region in the past have been referred to the above form, but the identification of this specimen is questionable. The teeth examined in the McPherson College Museum belong to *Parelephas columbi*.

P. columbi (Falconer).—Reported by Hay[34] from the examination of a tooth. The tooth was taken from sand at a depth of 23 feet in a well in the city of McPherson. Harnly[35] reports the remains of a Columbian elephant from a sand pit 12 miles northwest of McPher-

[29] "Pleistocene Fossils from McPherson County, Kansas, 1921 to 1924," *Trans. Kan. Acad. Sci.*, Vol. XXXI (1928), p. 97.

[30] "Vertebrate Fossils from McPherson Equus Beds," *Trans. Kan. Acad. Sci.*, Vol. XXXVII (1934), p. 151.

[31] *Op. cit.*, p. 96.

[32] *Op. cit.*, pp. 115–17.

[33] *Op. cit.*, p. 96.

[34] *Op. cit.*, p. 71.

[35] "Vertebrate Fossils from McPherson Equus Beds," *Trans. Kan. Acad. Sci.*, Vol. XXXV (1932), p. 209.

son. This is the same area from which the sloth remains were recovered. In this region are a number of small sand and gravel pits.

Equus complicatus Leidy.—This form was first identified by Cope as *E. major* and reported by Lindahl,[36] Williston,[37] Hay,[38] Nininger,[39] and Harnly.[40] This horse was found associated with *Megalonyx leidyi*. Harnly reported a distal phalanx that is of questionable identity, especially if the other species of horses reported from that area are valid. Nininger also questions the identity of the single tooth that he, himself, reported.

Equus leidyi Hay.—Harnly[41] reports a typical tooth of the above form from a sand pit on the Hammann farm in the same area from which the sloth remains and *Equus complicatus* teeth have been taken.

Equus niobrarensis Hay.—Nininger[42] reports several teeth and a metacarpal of the above species from a sand pit west of McPherson.

Camelops kansanus Leidy.—This species is based upon a fragmentary vertebra reported by Harnly[43] from a sand pit northwest of McPherson, probably near the Hammann farm. The material reported by Nininger[44] from a sand pit 8 miles west of McPherson also represents this form, but the material reported from a point southeast of McPherson is questionable. The camel material reported by Hay,[45] that was taken at a depth of 35 feet from the McGill sand pit 2 miles east from the center of McPherson, represents the remains of Tertiary camels as indicated by the age of the deposit.

Bison occidentalis Lucas.—Reported by Nininger.[46] It is based upon a calcaneum and 2 humeri taken from sand pits. Harnly[47] reported the same species from a gravel bed near McPherson, represented by the fourth dorsal vertebra and part of a right ulna. The specific identification of these forms is questionable and should be

[36] *Op. cit.*

[37] *Op. cit.* (1897), p. 303; also *op. cit.* (1898), p. 92.

[38] *Op. cit.*, p. 141.

[39] *Op. cit.*

[40] *Op. cit.* (1934).

[41] *Op. cit.* (1932).

[42] *Op. cit.*, p. 97.

[43] *Op. cit.* (1932), p. 209.

[44] *Op. cit.*, p. 97.

[45] *Op. cit.*, p. 165.

[46] *Op. cit.*, p. 97.

[47] *Op. cit.* (1932), p. 209.

carefully studied. Hay[48] reports *Bison* sp. indet. from a lower tooth found associated with the tooth of *P. columbi* in a well in the city of McPherson.

A list of the invertebrates taken at a higher horizon from the pit with the *Megalonyx leidyi* skull were identified by R. Ellsworth. These are given as listed by Lindahl:[49]

Sphaerium striatum Lam.	*Anodonta* sp.
S. sulcatum Lam.	*Valvata tricarinata* Say
Pisidium abditum Halderman	*Gammarus* sp.

THE EMMA CREEK FORMATION OF McPHERSON COUNTY

Amebelodon cf. *fricki* Barbour.—R. E. Mohler[50] reported the lower jaws and vertebrae of an *Amebelodon* found in 1936 on the Ganson farm, 4 miles west and 3 miles north of Canton, McPherson County, Kansas. At the time the paper was presented, the assumed Pleistocene age of the specimen was questioned, and it was contended that it represented a true Tertiary form. The restoration of Mohler's specimen is very misleading as the entire symphysis, tusks, right molar, and the anterior part of the left molar have been restored, and, as Mohler states: "Imagination has been freely drawn upon in the restoration of the tusks." Mohler was apparently influenced greatly by the shape of the anterior portion of the lower jaw of *Mastodon americanus* in thus restoring this part of the specimen and then adding the shovel-like tusks. Fortunately, associated with the broken jaw was part of a tusk of an *Amebelodon* which must be considered as Pliocene in age. Heretofore, *Amebelodon* is known only from numerous fragmentary remains of tusks, teeth, etc., from the Middle Pliocene of Kansas. We have no record to date of the occurrence of *Amebelodon* in the Upper Pliocene. Therefore, until contrary evidence is at hand, the specimen from McPherson County should be considered as representing a form not later than Middle Pliocene in age. However, when this fauna is better known, it may be found to extend into the Upper Pliocene. A careful examination of the specimen revealed no

[48] *Op. cit.*, p. 194.

[49] *Op. cit.*, pp. 1–10.

[50] "A New *Amebelodon* for Kansas," *Trans. Kan. Acad. Sci.*, Vol. XLI (1938), pp. 219–21.

evidence of stream transportation or re-working. The specimen must be considered as having been in place and does not, therefore, represent re-worked material of older age deposited in a younger fill.

Tetralophodon elegans (Hay).—Hay[51] described *Gomphotherium elegans* from a lower left hindmost molar, U.S. National Museum No. 8255, which was found about 1908 at a depth of about 35 feet in a sand pit in Sec. 34, T. 19 S., R. 3 W., in McPherson County. He referred the material to the Sheridan beds or Equus beds. However, the tooth was taken from the Emma Creek formation, of Tertiary age, and not from the McPherson formation (restricted). Osborn[52] says of the geologic age of this specimen:

> The early Pleistocene age of this specimen is important if Hay is correct in attributing the type to the Sheridan formation which with Hay we have placed in the Aftonian, or *1st Interglacial* time. Such a recent age seems improbable when we consider the relative progressive condition of *T.* (*Morrillia*) *barbouri* of middle Pliocene age. We, therefore, regard this tooth as of middle (?) Pliocene age.

Equus (*Plesippus*) cf. *simplicidens* Cope.—Horse material from the Emma Creek has been very fragmentary and rare. In 1939 Frye collected a radius referable to the above species at the center of the south line of Sec. 11, T. 18 S., R. 3 W. Identification was based on two teeth, one a left P_2 No. 5517 recovered from test well No. C14, at a depth of 93 feet, located in the southwest corner of Sec. 20, T. 23 S., R. 2 W. These teeth come from the same horizon as the material in McPherson County.

CONCLUSION

The vertebrate fossils of McPherson County represent two distinct ages: (1) Pleistocene and (2) Pliocene.

The Pleistocene fauna is characterized by *Megalonyx* and *Equus*. It is believed that careful collecting and study of the Pleistocene vertebrates will bring to light more than one fauna. The *Equus complicatus* and *Megalonyx leidyi* fauna are characteristic of the McPherson formation (restricted), whereas *Bison* appears to occur in the overlying and younger loess.

[51] "Description of a New Species of Mastodon, *Gomphotherium elegans*, from the Pleistocene of Kansas," *Proc. U.S. Nat. Mus.*, Vol. LIII, No. 2198 (1917), pp. 219–21.

[52] "The *Proboscidea*," *Amer. Museum Press*, Vol. I (1936), pp. 372–73.

The fauna of the Emma Creek formation contains vertebrate fossils of Pliocene age. These fossils are not secondarily deposited but are in place in the formation. The horse material taken from the upper part of the Emma Creek is Upper Pliocene in age, while *Amebelodon*, taken from the lower channel gravels of the Emma Creek formation, indicates a deposit of Middle Pliocene age. It is apparent, therefore, that the evidence of the vertebrate fauna substantiates stratigraphic and physiographic evidence for a Middle and Upper Pliocene age for the Emma Creek formation.

WALL-ROCK ALTERATION AT NIGHT HAWK PENINSULAR MINE, NIGHT HAWK LAKE, ONTARIO

A. RODDICK BYERS
University of Saskatchewan

ABSTRACT

Ore bodies in the Night Hawk Peninsular Gold Mine lie in or near a stock of albite syenite intruding Keewatin lavas. The deposit consists of carbonate zones carrying disseminated sulphides and cut by auriferous quartz stringers. The geological and mineralogical features are briefly described, and the hydrothermal metasomatism of the syenite is discussed in detail. Chemical analyses of the fresh and altered phases of the syenite are given, and the chemical changes are graphically displayed.

INTRODUCTION

The Night Hawk Peninsular Gold Mine is situated at the extreme southwestern end of North Peninsula in Night Hawk Lake, Cody Township, Province of Ontario, and thus lies approximately 10 miles east of the gold-producing district of Porcupine.

The mine is developed by a main shaft to a depth of 440 feet, with levels at 80, 180, 300, and 425 feet vertical depth and by a winze to 630 feet. From 1924 to 1926, $566,709 in gold was produced; but, owing to the falling-off in grade of the ore, operations were suspended. During 1934 and 1935 an extensive development program was carried out to locate new ore bodies and also to determine the limits and grade of the known bodies. This led to a detailed study of the property, with special attention being paid to the various types of rock alteration associated with the gold values.

GEOLOGY OF THE DEPOSIT

The oldest bedrock of the mine area consists of highly metamorphosed basalt and andesite volcanic flows of Keewatin age. The flows have an average strike of N. 75° E. and a dip of 70° S. Intrusive into the flows is an irregular, stocklike mass of albite syenite and albite-syenite porphyry, the latter being a border phase of the former. This body occupies the central portion of the mine, and in it are located the more important ore bodies (Fig. 1). The albite syenite is lithologically similar to other acidic intrusives in the sur-

rounding district that belong to the Algoman period of igneous activity. Cutting the Keewatin flows, the albite syenite, and the ore bodies are dikes of quartz diabase that have undergone very little deformation or metamorphism. These dikes are probably of Keweenawan age.

All the rocks, with the exception of the diabase, are highly faulted. The faults fall into three major groups, namely: (1) a set that has

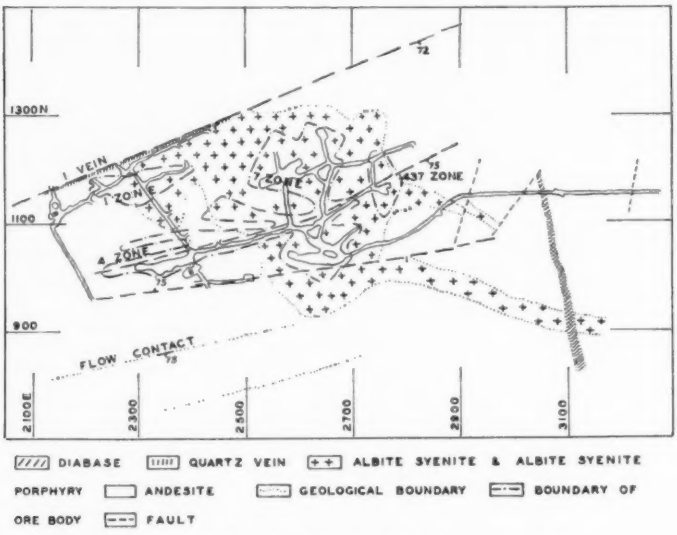


FIG. 1.—Geological plan of 425-foot level showing major relationships

an average strike of N. 70° E. and dip 75° S., (2) a group of low-angle (45°) easterly dipping faults which have an average strike of N. 20° E., and (3) a group of faults that strike N. 75° E. and dip 75° N. Field relations show that the No. 1 group are reverse, pre-ore faults, that the No. 2 set are reverse post-ore, and the No. 3 are normal faults that cut and displace both the No. 1 and the No. 2 sets.

The ore bodies are closely related to the No. 1 fault system, following shear and brecciation zones developed by the major faults of this system. Five ore bodies, whose boundaries are fairly well

known from drifting and diamond-drilling, occur in the developed area. With the exception of the No. 1 vein, which is a large quartz vein mineralized by later quartz-carrying gold, the ore bodies are carbonatized shear and brecciation zones carrying disseminated pyrite and arsenopyrite and cut by numerous irregular quartz veins which, in places, are numerous enough to form a stockwork. The ore bodies occur both in the andesite and in the albite syenite but attain the greatest size in the latter rock.

The mineralogy of the deposit is simple. Pyrite forms 90 per cent of the metallic minerals, and arsenopyrite, cobaltite, chalcopyrite, sphalerite, petzite, and gold occur in minor amounts. The gangue minerals are ankerite and quartz, with smaller amounts of sericite, chlorite, fuchsite, and albite.

The paragenesis of the ore as indicated by veining of the minerals by one another is as follows: During an early stage ankerite and some quartz replaced the rocks along fault zones belonging to the No. 1 system. The carbonatization was accompanied by the development of pyrite, arsenopyrite, and cobaltite, and, toward the end, by sericite, fuchsite, and chlorite. A second stage was initiated by a period of minor faulting and fracturing. Sericite, fuchsite, and chlorite continued to be formed during the early part of this stage. The fractures were filled by quartz and minor amounts of ankerite. Associated with these veins are pyrite and albite. The beginning of a third stage is marked by renewed fracturing which fissured all previously formed quartz veins and the replaced rocks. These fissures are filled by calcite and a little quartz and contain small amounts of chalcopyrite, sphalerite, petzite, and gold, which were formed in the order named. Figure 2 summarizes the observations of the paragenesis in the Night Hawk ore bodies.

WALL-ROCK ALTERATION

Inasmuch as the largest ore bodies are in the albite syenite, and as this rock may be presumed to have been originally fairly uniform in character, it was chosen for a detailed study of the alteration effected by the ore-depositing agencies.

The unaltered syenite contains albite as the essential mineral, with accessory quartz, quartz and albite in micrographic inter-

growth, microcline, apatite, biotite, hematite, and titaniferous-magnetite. The albite, $Ab_{94}An_6$ to $Ab_{90}An_{10}$, is fresh in appearance and forms over 70 per cent of the rock. It occurs either as well-developed euhedral laths or in anhedra with sutured interlocking boundaries. Quartz, which never forms more than 10 per cent of the rock, occurs as clear, unaltered grains filling interstices between the grains of feldspar. Frequently the quartz and albite have crystallized simultaneously to produce the so-called micrographic

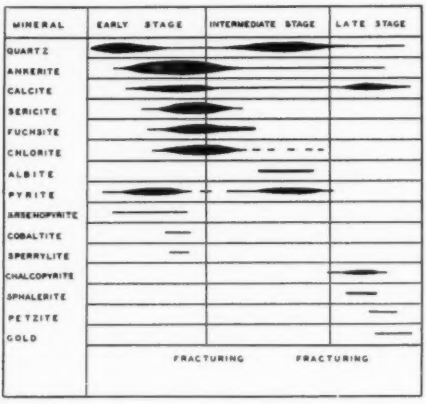


FIG. 2.—Paragenesis

or granophyric structure. Microcline is rare. Apatite does not exceed 3 per cent and occurs as small colorless needles. Biotite in irregular-shaped plates is deeply colored and has a marked pleochroism. Rutile, hematite, and magnetite occur as small, irregular grains scattered throughout the rock.

The average granularity is 0.5 mm. The fabric is either equigranular or porphyritic. The equigranular variety has a hypidiomorphic or granitoid texture. In the porphyritic variety the phenocrysts are well-developed euhedral crystals of albite. The texture of the groundmass may be either hypidiomorphic or allotrimorphic.

For the purpose of description and discussion, the various types of alteration that the syenite has undergone will be treated under the following headings: carbonatization, sericitization, fuchsitiza-

tion, and chloritization. Although treated as such, it should be clearly understood that these processes were going on in part simultaneously and represent a more or less continuous sequence of alterations of the syenite during the period of mineralization.

CARBONATIZATION

Carbonate alteration with the development of pyrite is the dominant and most characteristic metasomatic process connected with the deposition of the gold values. Intense carbonatization of the syenite is limited to the ore zones, and this type of alteration rapidly fades once the outer limits of the bodies are passed. The syenite becomes slightly darkened through the formation of a light-brown ankerite, and the carbonatized rock of the ore bodies is locally termed "brown carbonate." The altered syenite is seen in thin section to consist of carbonate commonly in rhombohedrons, with varying proportions of pyrite, sericite, quartz, chlorite, leucoxene, and, in some sections, fuchsite.

The carbonate is of two distinct varieties. One is a pale-brown ankerite which occurs in either well-developed rhombs or irregular masses replacing all the original constituents of the rock. The ankerite is pale brown, uniaxial, negative, with very high birefringence. Refractive indices, No = 1.690, Ne = 1.515. The other carbonate is a clear, colorless calcite which invariably takes the rhombohedral form. The ankerite was the first to form and belongs to an early stage in the period of replacement; the calcite was much later and is found in small veinlets cutting the earlier carbonate. Pyrite occurs in well-developed cubes scattered through the rock. Sericite, chlorite, and fuchsite occur as very fine anastomosing veinlets. Quartz, which is usually clear, occurs either in small veinlets or as a replacement of the original constituents, in which case it forms a fine-grained mosaic of interlocking grains. Leucoxene occurs in varying amounts, depending on the percentage of the original ilmenite and magnetite in the syenite.

SERICITIZATION

Sericitization, or potash metasomatism, accompanies the carbonatization of the syenite and is a characteristic feature of the ore bodies. In the course of the metasomatic process, the biotite and

feldspars of the syenite are vigorously attacked. The alteration proceeds along cracks or cleavage planes, and a finely felted aggregate of sericite and ankerite invades the grains until in the highest stage the replacement is complete. Even the quartz is partially replaced.

The sericite occurs as very fine scales or fibers. The flakes are too small to obtain many of its optical properties. It is colorless or may have a faint pinkish tinge. The birefringence is very strong. The index of refraction, Nm is 1.585. In places the sericite grades into fuchsite, Cr_2O_3 replacing part of the Al_2O_3, and the mineral takes on a greenish tinge. Toward the margins of the lodes the sericite becomes less abundant, and chlorite commences to take its place until in the areas immediately surrounding the ore bodies the sericite has completely disappeared, and chlorite has become abundantly developed in its place.

FUCHSITIZATION

In certain sections of the ore zones the carbonate rock contains minute flakes of a bright-green mica which imparts a green color to the rock, which is then called "green carbonate." The green mica was determined as fuchsite, a chromiferous muscovite, the presence of chromium being determined by chemical analysis. The color varies from light emerald green to almost colorless, pleochroism is very weak or entirely absent, birefringence 0.038, elongation positive, biaxial and negative, $2V = 48°–50°$. Refractive index $> 1.590 < 1.5987$.

The relation of the fuchsite to the brown carbonate and to the other minerals is indicated both microscopically and megascopically by veining and cutting of the minerals by one another. A series of thin sections taken across a band of green carbonate cutting the brown carbonate rock of the ore zone show: (1) The fuchsite is later than the main period of ankeritization but older than the period during which gold deposition took place; and (2) the solutions which introduced the fuchsite, at the same time, leached the pyrite and, carrying it off in solution, deposited it outside the area of green carbonate rock.

Wherever the fuchsite alteration has affected the carbonate

rock, the gold values are low. This cannot be explained by a leaching of the gold similar to the pyrite, since the deposition of the gold is definitely later than the fuchsitization. The almost complete absence of pyrite from the green carbonate zones suggests that this mineral exerted an important influence favoring the precipitation of gold. On the other hand, it may be argued that the presence of fuchsite in some manner tended to prevent the gold from being deposited. However, the fact that a large percentage of the gold observed in polished sections of the ore is closely associated with pyrite around the edges and in small fissures cutting the pyrite grains would indicate that it was the pyrite and not the fuchsite which influenced the precipitation of the gold.

CHLORITIZATION

In the vicinity of the ore bodies, immediately outside of the brown carbonate zones, the syenite is largely replaced by chlorite. The chlorite may or may not occur in very minor amounts within the ore zones, where it occupies small fractures and cleavage planes. As the margins of the lodes are approached and the gold values become lower, the chlorite increases in amount, until away from the ore bodies the syenite becomes highly chloritized. This transition is usually abrupt, taking place over a distance of a few feet, so that in many places the ore boundaries are distinct.

The chlorite is pale green and occasionally has weak pleochroism—$X = Y =$ green, $Z =$ colorless. In many sections it shows "ultra blue" abnormal-interference colors. It is positive, with $2V = 0° - 4°$. There is apparently no difference in the optical properties of the chlorite found in the ore and that occurring in the country rock outside the lodes.

Briefly summarizing the metasomatic alterations affecting the syenite during mineralization, it may be said that carbonatization (ankeritization) has been the dominant process by which the syenite was altered within the zone of gold mineralization. Second in importance has been sericitization with fuchsite sometimes being developed in its place. The chloritization of the syenite has been the dominant alteration immediately outside the ore bodies (Fig. 3).

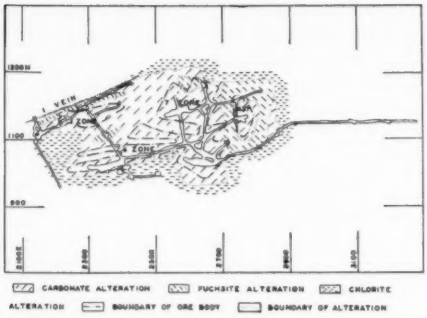


FIG. 3.—Plan of 425-foot level showing relation between ore and alteration zones

TABLE 1

CHEMICAL ANALYSES OF FRESH AND ALTERED PHASES OF SYENITE

	1	2	3	4	1a	2a	3a	4a
SiO_2	60.87	35.77	46.20	48.60	162.52	101.69	126.40	136.76
TiO_2	0.62	0.32	0.71	0.76	1.65	0.91	1.94	2.13
Al_2O_3	19.40	9.27	15.20	20.39	51.79	26.35	41.58	58.76
Cr_2O_3	0.00	0.25	0.01	0.00	0.00	0.71	0.03	0.00
Fe_2O_3	0.96	0.43	0.73	1.13	2.56	1.22	1.99	3.17
FeO	0.32	3.83	3.43	5.65	0.85	10.98	9.38	15.89
MgO	1.23	9.10	4.86	5.22	3.28	25.87	13.29	14.68
CaO	3.13	15.60	8.91	5.95	8.35	44.35	24.37	16.74
Na_2O	9.26	0.06	2.34	2.64	24.72	0.17	6.30	7.42
K_2O	0.18	2.77	2.38	0.26	0.48	7.88	6.51	0.73
MnO	0.02	0.17	0.13	0.13	0.05	0.48	0.35	0.36
H_2O	0.53	1.67	1.93	1.98	1.41	4.74	5.28	5.57
CO_2	3.04	19.90	12.01	6.15	8.11	56.57	32.86	17.31
S	0.41	0.06	1.25	0.88	1.09	0.17	3.42	2.47
Total	99.97	99.20	100.09	99.74	266.86	282.09	272.70	281.09
Spec. grav.	2.670	2.843	2.736	2.814	.....	.....	.....	.....

No. 1—Fresh, relatively unaltered, albite syenite.

No. 2.—Green carbonate—carbonatized albite syenite containing fuchsite.

No. 3.—Brown carbonate—altered albite syenite, typically developed in the ore bodies.

No. 4.—Chloritized albite syenite—typical of the altered syenite immediately outside the ore bodies.

Nos. 1*a*–4*a*.—Constituents of the above rocks, in grams in 100 ccm. of rock.

CHEMICAL ANALYSES

The writer had four analyses made: one of the relatively unaltered syenite, a second of the green carbonate or fuchsite-sericite carbonate rock, a third of the brown carbonate or ankerite-sericite rock typical of the ore bodies, and a fourth of the chloritized rock immediately outside the ore zone. In all cases representative samples were selected that were entirely free of vein material and consisted only of the altered rock. Mr. M. F. Connor, of Ottawa, made the analyses, the results of which are given in Table 1, columns 1–4.

The most instructive kind of comparison between fresh and altered rock is one that will show quantitatively what constituents have been added to or subtracted from a known volume of the fresh material during alteration. The chemical analyses expressed in columns 1–4 represent the composition of equal weights of material. As the summation of each analysis is very close to 100, the multiplication of the figures of each analysis by the specific gravity of the respective rocks will give approximately the weight in grams of each constituent contained in 100 ccm. of each of the four varieties of rock. The results of this multiplication are shown in columns 1*a*, 2*a*, 3*a*, and 4*a*.

The chemical changes in the rock are graphically displayed in Figures 4, 5, and 6, which compare the items in column 1*a* with those in 2*a*, 3*a*, and 4*a*, successively. In the diagrams, if the figure for any radical is a square, it signifies no change in that radical. Departure from the square shows a gain or loss; thus in Figure 4 the great loss in Na_2O and gain in CaO are clearly indicated.

The important facts brought out are the notable decrease in silica, soda, and alumina, with the exception of the chloritized syenite, in which case some alumina has been added. This decrease in the above constituents is accompanied by a large increase in ferrous iron, magnesia, lime, potash, and water. Carbon dioxide has been added in large amounts. Cr_2O_3 is not found in the unaltered rock and has been added to the green carbonate and, to a much lesser extent, to the brown carbonate and not at all to the chloritized syenite. Ferric iron is decreased in the first two types but increased slightly in the chloritized rock. MnO has been added in all three

types of alteration. Sulphur is very low in the green carbonate, as would be expected, since microscopical study of this rock type

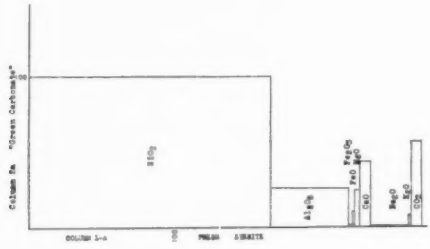


FIG. 4

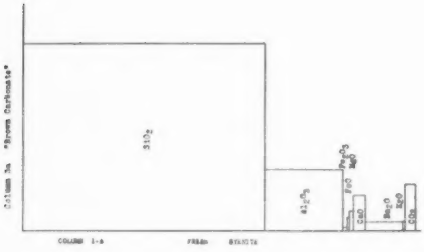


FIG. 5

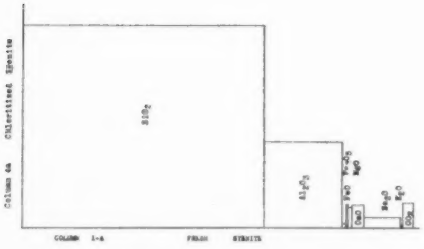


FIG. 6

showed that pyrite was leached and redeposited outside the fuchsite zone. Increases in the percentage of sulphur have taken place in the other two types, notably in the brown carbonate.

CHARACTER OF THE ORE SOLUTIONS

If the alteration of the albite syenite was effected by the continuous action of solutions of one kind and origin, it appears that these were rich in the bicarbonates of iron, magnesia, lime, potash, and manganese, but poor in silica and soda. They also carried sulphur, chromium, and free carbon dioxide.

Regarding the precise nature of the mineralizing solutions which deposited the gold, there is, of course, no direct information. They must certainly have been aqueous and have been competent to cause replacement by carbonates, sericite, pyrite, etc., and capable of carrying metallic elements such as copper, gold, tellurium, zinc, and iron.

It is evident from a comparison of the chemical analyses of the fresh and altered rocks that there has been a subtraction from the rock of silica, alumina, and soda and an addition of calcium, magnesium, potassium, iron, and sulphur, which went to form ankerite, calcite, sericite, and pyrite. The solutions which effected the metasomatic alteration of the albite syenite, therefore, originally contained an abundance of carbon dioxide, hydrogen sulphide, and potash. In the course of time, as the result of their metasomatic action, the solutions would become poorer in iron, magnesia, and lime and richer in alumina, silica, and chromium. Still later, during the deposition of the gold, the solutions, as inferred from the minerals contained in the quartz-carbonate veinlets, contained Au, Zn, Te, Cu, Fe, CO_2, CaO, and S. These results indicate hot ascending solutions having a variable amount of alkaline carbonates, free carbon dioxide, and invariably much sulphur. It follows, therefore, that they were either neutral or alkaline but not acidic solutions. Since the sulphides, chalcopyrite, sphalerite, and pyrite were being deposited at approximately the same time as the gold, the mineralizing agents were in all probability hot alkali hydrosulphide or alkaline sulphosalt solutions. The gold would be carried as a double sulphide of the alkali metal or as an alkaline sulphosalt. Oxidation, acidification, changes in pressure and temperature, and the presence of pyrite and other sulphides would cause the precipitation of the gold.

O. C. Schmedeman,[1] in a recent paper, reached the tentative conclusion that ore solutions are originally acid and become neutral or alkaline only after reaction with their channel walls and at a considerable distance from their source. He recognizes, however, that the usual deep-seated, gold-quartz type of wall-rock alteration does not fit into his general theory, and he implies that (1) either they are not near source even though they are recognized as being deep-seated; (2) or that the mineralizing solutions are from the beginning of a fundamentally different nature from those that form the deposits of the shallower zones—a consequence of deeper-seated, more extended differentiation in the parent-magma.

Although there is no direct evidence of the nearness of the magma from which the solutions that formed the ore bodies in the Night Hawk Mine originated, it is more than probable that large intrusive bodies underlie the immediate area at relatively shallow depths. Large, intrusive, batholithic bodies of granite and related rocks occur at a distance of only 12 miles south of Night Hawk Lake in the townships of Thomas, Blackstock, and Langmuir. The presence of numerous syenite dikes and other small bodies of related rocks in the immediate area would indicate that a large body of magma underlay the area at no very great depth during the Algoman period of igneous activity and gold mineralization. It is more than probable, therefore, that the Night Hawk deposits are relatively near source, and, consequently, the second supposition of Schmedeman would appear more reasonable, namely, that the mineralizing solutions are of a fundamentally different nature, owing to deeper and more prolonged differentiation in the parent-magma.

SUMMARY AND CONCLUSIONS

In the Night Hawk Mine the ore bodies are found in or near a small stock of albite syenite which intrudes steeply dipping, Keewatin andesite flows. With one exception the ore bodies are carbonatized shear and brecciation zones with disseminated sulphides cut by quartz veins which, in places, are numerous enough to form a stockwork.

[1] "Notes on the Chemistry of Ore Solutions," *Econ. Geol.*, Vol. XXXIII (December, 1938), pp. 796–97.

Carbonate alteration (ankeritization) is the dominant type of wall-rock alteration. It has affected large volumes of the syenite and is most intensely developed within the zones of gold mineralization. Second in importance and more or less accompanying the carbonatization is the development of sericite and fuchsite. Chloritization affects a zone of rock around the margins of the carbonate bodies. It is intense close to the carbonatized zones and gradually decreases away from them.

Chemical analyses of the unaltered and altered syenite show a large decrease in SiO_2, Na_2O, and Al_2O_3, with the exception of the chloritized syenite, in which case some Al_2O_3 has been added. This decrease is accompanied by an increase in FeO, MgO, CaO, and K_2O.

From the nature of the mineralization and the wall-rock alteration, it may be concluded that the mineralizing solutions were, in all probability, very dilute, hot, alkaline waters containing carbon dioxide, alkaline carbonates, and hydrogen sulphide as their main constituents. The gold was transported as a double sulphide of the alkali metals or as an alkaline sulphosalt.

The deposit is considered to be near source, and the alkaline nature of the ore solutions is therefore due to a special differentiation in the parent-magma that is peculiar to deep-seated gold deposits.

ACKNOWLEDGMENTS.—The writer wishes to express his sincere thanks to Drs. J. E. Gill and W. F. James for financial assistance and for the opportunity to make a detailed study of the geology of the Night Hawk Peninsular Mine; to Dr. Gill for his kind advice and guidance during the preparation of this paper; and to Dr. B. S. W. Buffam for his counsel and assistance at the mine. The writer also wishes to acknowledge his indebtedness to Drs. R. P. D. Graham and F. F. Osborne for criticism and assistance in the laboratory at McGill University.

STUDIES FOR STUDENTS

A NEW PROJECTION PROTRACTOR. I

D. JEROME FISHER
University of Chicago

ABSTRACT

The instrument herewith described is an aid in the rapid preparation and interpretation of stereographic and gnomonic projections for a fundamental sphere of radius either 5 or 2 cm. The use of the instrument in solving distance, angle, rotation, and reflection problems is described in elementary fashion illustrated by simple examples. Application of these to the solution of problems in structural geology and morphological crystallography is brought out.

Introduction
The instrument
Definitions
Stereographic projection
Gnomonic projection
The two projections
Distance problem
  Stereographic solution
  Gnomonic solution
Projection symbolism and relations
Applications of the distance problem
  Crystallography
  Geology
  Other sciences
Angle problem
More difficult examples of distance and angle problems
Measuring angles in the gnomonogram
Rotation problem
  Rotation axis normal to the primitive
  Rotation axis parallel to the primitive
  Rotational axis neither normal nor parallel to the primitive (hemitrope)
Reflection twin
Crystal drawing

INTRODUCTION

For the serious study of morphological, optical, and X-ray crystallography it is generally agreed that both gnomonic and stereographic projections are nearly essential.[1] The latter is the more fundamental

[1] This does not mean that the use of other projections is ruled out. Thus see F. E. Wright, "The Methods of Petrographic Microscopic Research," *Carnegie Inst. of Wash. Pub. No. 158* (1911), pp. 63–68. The Lambert equal-area meridian projection used in petrofabrics is described in C. H. Deetz and O. S. Adams, "Elements of Map Projection," *U.S. Coast and Geodetic Surv. Special Pub. No. 68* (1938), pp. 73,

from this point of view, since it embraces all possible cases. But where the work can be limited to planes which are either vertical or at least 10° or 15° off vertical, the gnomonic projection is generally simpler; it thus suffices for many morphological studies of untwinned crystals and is well-nigh indispensable in calculating indices and preparing drawings. Moreover, the use of some principles of the gnomonic projection is of great help in preparing a stereographic projection. For these reasons there is herewith described a modified form of protractor which is of considerable aid in the rapid preparation and interpretation of these two projections. More or less similar protractors have been described by earlier workers, such as A. Harker,[2] S. L. Penfield, E. Federow,[3] V. Goldschmidt and F. E. Wright,[3] A. Hutchinson, and especially T. V. Barker.

Since problems in several fields besides crystallography, including structural, metamorphic, and mining geology as well as cartography (photogrammetry), seismology, navigation, astronomy, perspective projection, etc., may be solved simply with the protractor, and because those related to maps are probably closest to everyday experience, these last are here used for illustrative purposes in the first part of the paper, where a given type of solution is first encountered. Moreover, since it has been the writer's teaching experience that with the average student the most successful approach is to do something (practice), then see why it was so done (theory), the paper consists of a series of such steps. Purely mathematical treatment is avoided, since other publications which can be traced down by means of the references listed are adequate from this point of view; they should be consulted for proof of some of the statements here made. In short, besides describing a new instrument, the object of this paper is to show in the simplest possible manner and with some

---

75–76. Other references are listed in W. E. Ford, *Dana's Textbook of Mineralogy* (New York: John Wiley & Sons, 1932), p. 60; in A. Johannsen, *Manual of Petrographic Methods* (New York: McGraw-Hill Book Co., 1918), pp. 5–28; also elsewhere in this paper.

[2] "The Use of the Protractor in Field Geology," *Sci. Proc. Roy. Dublin Soc.*, Vol. VIII (1893), pp. 12–20.

[3] "Die Wichtigkeit der Anwendung des stereographischen Lineals," *Zeitschr. Krist.*, Vol. XLIV (1908), p. 89; and "Ein Projections-Transporteur," *ibid.*, Vol. XLV (1908), p. 569.

repetition how it can be used to advantage by beginning workers in a number of geological fields. Where several alternative solutions of a given problem are described, all but the first may be omitted by the beginner on his first "trip" through the paper. Alternatives are desirable for the experienced worker, since the handiest type of solution will vary under different circumstances.

THE INSTRUMENT

The new projection protractor (Fig. 1) is a $7\frac{1}{2} \times 20$-cm. rectangle of 0.020-inch thick colorless transparent vinylite printed in red in reverse position; the printing is protected by a 0.003-inch thick lamination of vinylite. The upper two-thirds of it embraces half a meridian stereographic net (commonly known as the "Wulff net") of radius 5 cm. in the left half, together with gnomonic and stereographic scales for this size sphere along the top edge of the protractor tangent to the net. The gnomonic scale serves as part of an ordinary protractor of 5–15-cm. radius, which is extended to 180° along the two ends. It is graduated to $\frac{1}{2}$° intervals (to $\frac{1}{4}$° intervals along its right half from 45° to 90°). Continuous with the axis (polar diameter) of the net (parallel the top edge of the protractor) is a scale of radii for the circles of the net. There is a metric scale graduated to half-millimeters from 10 to 19 cm. in the upper right portion of the protractor. The graduations are measured from the left end of the protractor, and so the position of the 10-unit lies 5 cm. to the right of the equator of the net. It is important to use this centimeter scale, since any shrinkage of the vinylite should be essentially uniform for the net and all scales of the projection protractor. In working with the instrument keep the printed (laminated) side against the paper to avoid parallax.

The lower one-third of the protractor duplicates a portion of the upper part at a smaller scale (radius = 2 cm.).[4] It contains half a meridian stereographic net drawn to 5° intervals (useful in connection with the numerous stereographic drawings to this scale in the

[4] Because of space limitations, stereographic-degree values (which are exactly double the gnomonic ones) are omitted from the lower scale of the protractor. For the same reason the scale of radii is marked only for small circles, but by taking complementary values great-circle data are given.

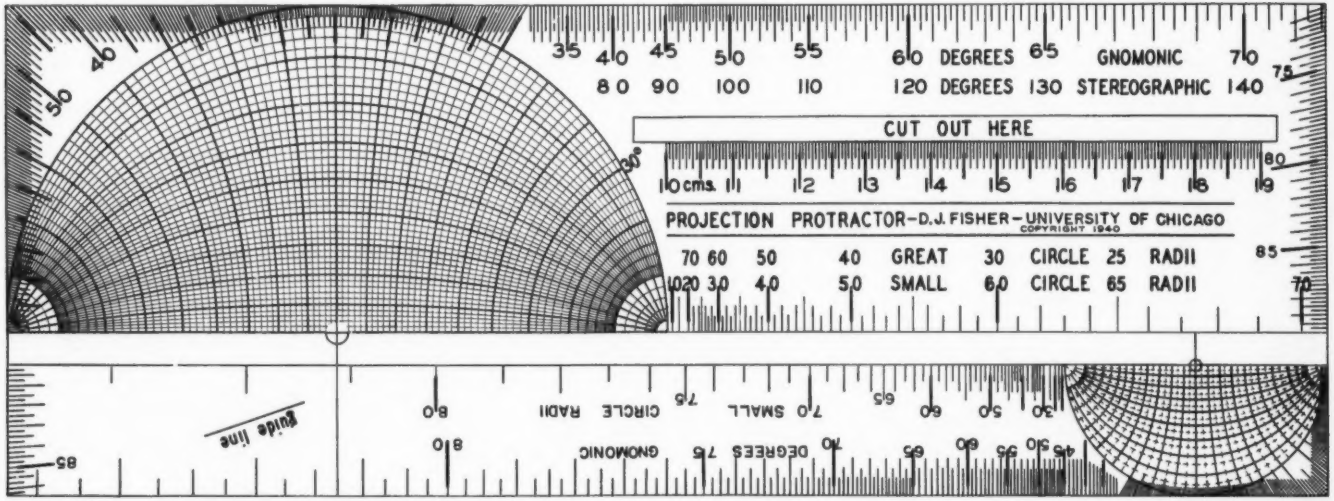

35 40 45 50 55 60 DEGREES 65 GNOMONIC 70 75
80 90 100 110 120 DEGREES 130 STEREOGRAPHIC 140
CUT OUT HERE
0 cms. 1 1 2 3 4 5 6 7 8 9
PROJECTION PROTRACTOR-D.J. FISHER-UNIVERSITY OF CHICAGO
COPYRIGHT 1940
70 60 50 40 GREAT 30 CIRCLE 25 RADII
10 20 30 40 50 SMALL 60 CIRCLE 65 RADII
guide line
CIRCLE RADII
SMALL
GNOMONIC
DEGREES

FIG. 1.—The new projection protractor. This embraces: (1) an ordinary semicircular protractor; (2) a centimeter scale; (3) stereographic and gnomonic scales where the radii of the fundamental spheres are 5 and 2 cm.; (4) semicircular meridian stereographic (Wulff) nets for these spheres; and (5) scales for radii of great and small circles of these spheres in stereographic projection.

various volumes of the *Strukturbericht*).[5] The lower gnomonic scale permits plotting of angles up to 83°40′ from the center (71°34′ is the limit on the upper scale); it is used in any specific case where the upper scale is too limited. Since its mode of utilization is the same as that of the upper scale, the following discussion refers only to the upper two-thirds of the protractor which (for the sake of simplicity) is all that is shown in the later diagrams. Some may even prefer to cut the protractor into two separate instruments; if this is done, a projecting portion should be left at *C* (Fig. 2), so that the net may be rotated about a needle at *C*.

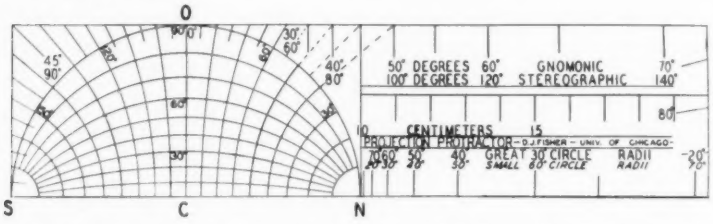


FIG. 2.—Skeleton form of the 5-cm. radius part of the projection protractor. The poles of the semicircular meridian stereographic net are shown by *N* and *S;* its center is at *C; CO* is its half-equator. The zero point of the upper (stereographic and gnomonic) scale is at *O*.

DEFINITIONS

Definitions of technical terms employed in this paper are here grouped in alphabetical order for convenience of reference. This list can best be used during the study of what follows. Some of the definitions are explained by letters referring to the gnomonostereogram of Figures 10 and 11 where point *Z* of polar distance ρ (measured in gnomonic degrees) lies on radius *OZ* (part of extended diameter *DE*) of the primitive, and point *W* of polar distance 2θ (measured in stereographic degrees) lies on *ZO* extended. *ZV* is normal to *ZW*. (Note that $\rho + 2\theta = 90°$, as is shown in the vertical cross section of Fig. 9.)

Angle-point.—Point that serves as vertex for an angle in the projection plane which is the true angle between two points that lie on the sides of the angle

[5] Cf. E. Brandenberger, *Angewandte Kristallstrukturlehre* (Berlin: Gebrüder Borntraeger, 1938), pp. 108–13.

and along a definite great circle which is normal to the diameter of the primitive through the angle-point. Designated by W (German: *Winkelpunkt*). The *gnomonic* angle-point for line ZV (where the polar angle of point $Z = \rho = 90 - 2\theta$ measured in gnomonic degrees) lies at W where $OW = 90 - \rho = 2\theta$ measured in stereographic degrees (cf. line of centers). W is also the *stereographic* angle-point as well as the pole of arc $C'V''W'$. Just as W is the gnomonic angle-point for line ZV, the latter is the stereographic line of centers for point W.

Antipodal point.—A point on the fundamental sphere diametrically opposite any given point. The two points have supplementary polar distances and when projected lie on the same diameter of the primitive.

Center of projection.—Point from which radiate lines (called projectors) normal to planes (gnomonic only) or through points on the surface of the fundamental sphere, or through other points being projected.

Curve of poles.—Circle in the gnomonogram which is the locus of all points, one of which lies on each diameter of the primitive 90° from the point where it intersects a given zone-line (great circle); each zone-line thus has its characteristic curve of poles.

Cyclographic projection.—Analogous to the stereographic except that planes are projected not as face-poles but as great circles marking the intersection of these planes (moved parallel themselves until they go through the center of the fundamental sphere) with the surface of the fundamental sphere.

Edge-pole.—See "zone-axis."

Equator projection.—One in which the plane of projection is parallel the equator; called "polar projection" by some writers.

Euthygraphic projection.—Analogous to the gnomonic except that planes are projected not as face-poles but as lines marking the intersection of these planes (moved parallel themselves until they go through the center of the fundamental sphere) with the plane of projection.

Face-pole.—A point on the fundamental sphere where it is cut by a radius normal to the face or plane in question; a point in the plane of projection where cut by the projector through a face-pole on the fundamental sphere.

Fundamental sphere.—The sphere whose surface is being projected; also refers to a sphere the radius of which determines the scale of the projection (assuming the plane of projection bears a fixed relationship to the fundamental sphere); also called the primitive, basic, or unit sphere by some writers.

Gnomonic projection.—One in which the center of projection is at the center of the fundamental sphere; planes are projected as points (face-poles) located by projectors normal to the planes in question. The plane of gnomonic projection is tangent to the fundamental sphere at its north pole.

Gnomonogram.—A gnomonic (or euthygraphic) projection.

Gnomonostereogram.—A combined gnomonic and stereographic projection in which the plane of projection is that of the gnomonic projection; thus in this case the plane of stereographic projection, here taken as the equatorial plane of the fundamental sphere, is considered as projected orthographically to the plane of gnomonic projection.

Great circle.—Any circle made by the intersection of a plane through the center of the fundamental sphere with this spherical surface; also the projection of such a circle; its polar distance is 90°; it is a straight line in the gnomonic projection. If one great circle passes through the pole of another great circle, the two great circles are mutually perpendicular. One complete great circle crosses another at two points which are antipodal. Only one great circle can be passed through any two nonantipodal points on a sphere.

Inclination of a circle.—The angle between its plane and that of the plane of projection; corresponds to dip angle of geologists in case the plane of projection is horizontal.

Line of centers.—Straight line in the stereographic projection which is the locus of the centers of all great circles passing through any given point; in both projections is normal to the line of measures (diameter of the primitive) through the given point; intersects the line of measures at the gnomonic zone-center; has the same significance as zone-line. The stereographic line of centers for point W of polar angle 2θ (measured in stereographic degrees) is ZV where the polar angle of point $Z = 90 - 2\theta = \rho$ measured in gnomonic degrees (cf. angle-point).

Line of measures.—That diameter of the primitive which passes through the pole of any given circle; also used for any diameter of the primitive normal to a line of centers; intersects the line of centers at the gnomonic zone-center; has the same significance as zone-central.

Meridian projection.—One in which the plane of projection is parallel a meridian (or normal to the equator).

Orthographic projection.—One in which the center of projection is at infinite distance from the fundamental sphere. In this paper the plane of orthographic projection is taken as tangent to the fundamental sphere at its north pole.

Phi (φ).—Greek letter used to designate the horizontal angle measured clockwise from the zero radius of the primitive to the radius on which a given point lies. In an equator projection the zero radius is taken as the east direction (map parlance); thus φ = longitude for west longitude, and $\varphi = 360° -$ longitude for east longitude.

Plane of projection.—The plane of the paper in a gnomonogram or stereogram; the plane onto which is being projected the surface of the fundamental sphere, or a series of crystal faces and directions, or whatever is being projected; also called the primitive plane by some writers.

Polar distance of a circle.—Angular distance along a great circle on the surface of the fundamental sphere from the nearest pole of the circle in question to any point on its circumference; this is always 90° for great circles.

Polar distance of a point.—Angular distance along a great circle on the surface of the fundamental sphere from the pole of the primitive to any given point; designated by ρ.

Poles.—The two points on the surface of the fundamental sphere where it is cut by a diameter of the sphere normal to the plane of any circle (great or small). The poles of a great circle are 90° from any point on its circumference. P and F (note that F is in a tiny triangle to show that it represents a point on the lower hemisphere) are the gnomonic poles of VZ, while W and D are the stereographic poles of $C'V''W'$. Thus $PF = 180°$ gnom. and $WD = 180°$ ster.

Primitive.—The primitive circle in the plane of projection. It is the diametral cross section of the fundamental sphere parallel the plane of projection. The center of the primitive coincides with the point cut by a projector normal to the plane of projection.

Projector.—See "center of projection."

Rho (ρ).—Greek letter used to designate the angle of polar distance of a point (*q.v.*); for an equator projection corresponds to (90° − Lat.) for the northern hemisphere, (90° + Lat.) for the southern. Also see θ.

Small circle.—Any circle on a sphere not a great circle; thus any circle made by the intersection with the spherical surface of a plane that does not go through the center of the fundamental sphere.

Stereogram.—A stereographic (or cyclographic) projection.

Stereographic projection.—One in which the center of projection is on the surface of the fundamental sphere; planes are projected as points located from face-poles on the fundamental sphere where cut by radii normal to the planes in question. In this paper the plane of stereographic projection is taken as the equatorial plane of the fundamental sphere, although it is considered that this plane is projected orthographically to the plane of gnomonic projection in gnomonostereograms.

Theta (θ).—Greek letter used to designate an angle of polar distance of an auxiliary point; so related to ρ that $\theta = \frac{1}{2}(90° - \rho)$ or $\rho = 90° - 2\theta$.

Zone.—All the faces on a crystal parallel a single direction. If such faces meet, their edges are also parallel this direction, the zone-axis.

Zone-axis.—Direction parallel two or more crystal faces; also applied to the projection of this direction, though this latter is better termed "edge-pole."

Zone-center.—Point of intersection of a zone-line with its zone-central; also used in this paper for the point of intersection of a line of measures with a line of centers.

Zone-central.—Diameter of the primitive normal to a zone-line in crystallography; also used in this paper with the same significance as line of measures.

Zone-line.—Euthygraphic or cyclographic projection of the plane normal to a zone-axis in crystallography; in general any great circle in these projections; may coincide with a line of centers.

STEREOGRAPHIC PROJECTION

When points (or lines) on the surface of a transparent sphere (the fundamental sphere) observed by the eye held at some point (called the center of projection) on the surface of the sphere are plotted as they appear on a plane (the plane of projection) normal to the line joining the eye and the center of the sphere, the result is a stereographic projection. The net occupying the major portion of the left half of the protractor is such a projection of the parallels (horizontal small circles) and meridians (vertical great circles) drawn to 2° intervals on one-quarter of a 5-cm. radius terrestrial globe (0°–90° longitude). The eye is held on the equator where crossed by the meridian of 180° (about 1,100 miles north of the Fiji Islands) and the north pole of the net (*N* of Fig. 2) lies just below the center of the protractor. Since the projection plane is that of the 90° meridian, the net is called a meridian stereographic net.

The small circles are counted down from the north pole (to 180° at the south pole) rather than up and down from the equator as is done for latitude on a terrestrial globe. This is indicated on the skeleton form of the protractor given in Figure 2 at a reduced scale. The small circles normal to the meridians of this net may be duplicated from the scale of small-circle radii of the protractor by placing the needle of a compass on the appropriate graduation of the scale and its pen point or pencil edge on the corresponding circle of the net (see Fig. 3, *a*). However, if the circle lies between 70° and 90°, its radius is too large to be shown on the scale,[6] and it is more easily drawn by means of an adjustable-curve ruler; or it may be traced from the net.

To duplicate the great circles of the net complementary values on

[6] The distances (in cm.) from the north pole of the net to the centers of these small circles are as follows (formula is: $d = 5/\cos \alpha - 5$):

71°–10.4	76°–15.7	81°–27.0	86°– 67.2
72 –11.2	77 –17.2	82 –30.9	87 – 90.5
73 –12.1	78 –19.0	83 –36.0	88 –138.3
74 –13.1	79 –21.2	84 –42.8	89 –281.5
75 –14.3	80 –23.8	85 –52.4	90 – ∞

the same scale are given as appropriate distances from the center of the net. Thus, to reproduce the 40° great circle of the net (out 40° from the axis of the net measured along the equator [see Fig. 2]), place the center of the net 40° from the center of the given projection as shown in Figure 4, *a*. The center of the desired great circle is then found at the 40° graduation on the scale of the great-circle radii. Or this center may be found even more simply by placing the top scale of the protractor along a diameter of the given projection with its zero point (*O* of Fig. 2) at the center of the primitive circle and counting out from the center the complementary distance in gnomonic degrees.[7] This is illustrated in Figure 4, *b*, for the 30° great circle (the center of this great circle is out 90°–30° = 60° measured on the gnomonic scale from the center of the primitive circle); the length of its radius is given by the distance from this center to the 30° point on the stereographic scale to the left of the zero point.[8]

It will be noted that the spacings of the graduations between *C* and *N* of Figure 2 are the same as those between *C* and *O*. They are also like the ones along the left end of the protractor and, moreover, are the same as those of the stereographic graduations along the top scale going out either way from *O*. In short, tangents to the small circles along the polar axis cut the upper scale at corresponding divisions in stereographic degrees, while tangents to the great circles along the equator cut the left end of the protractor at analogous points. Straight lines from *N* through these points of graduation on *CO* cut the arc of the great circle between *S* and *O* at 10° intervals. Also note that a tangent to the 90° meridian (outside circle) of the

[7] Since 71° gnomonic is the last integral graduation, the protractor suffices for drawing great circles down to 19°. For smaller values the following distances (in cm.) from the primitive circumference to the center of the great circle may be used (formula is: $d = 5 \cot a - 5$):

19°– 9.52	14°–15.05	9°28′–24.99	5°– 52.15
18 –10.39	13 –16.66	9 –26.57	4 – 66.50
17 –11.35	12 –18.52	8 –30.58	3 – 90.41
16 –12.44	11 –20.72	7 –35.72	2 –138.2
15 –13.66	10 –23.36	6 –42.57	1 –281.5

[8] In corresponding fashion the top scale may be used to find the centers of the small circles of the net as shown in Fig. 3, *b*, for the 60° small circle. Thus if this scale is placed along the polar axis of the net with its zero point on the 60° small circle of the net, its 60 gnomonic-degree point will lie at the 60° point of the small-circle radii scale.

net at the point of intersection of any given small circle (*ab* of Fig. 3, *a*) cuts the scale of small-circle radii at the center of the small circle in question, and the length of this tangent (from the 90° meridian to the scale of radii) is equal to the distance out from the center of the primitive circle to the center of the great circle of complementary

FIG. 3*b*.—Alternative method for drawing a small circle (60° in this case) in the stereographic projection. The zero point of the upper scale is the complement of 60° from the center of the primitive circle. The radius extends along the upper scale from its zero point to the 60° *gnom.* mark.

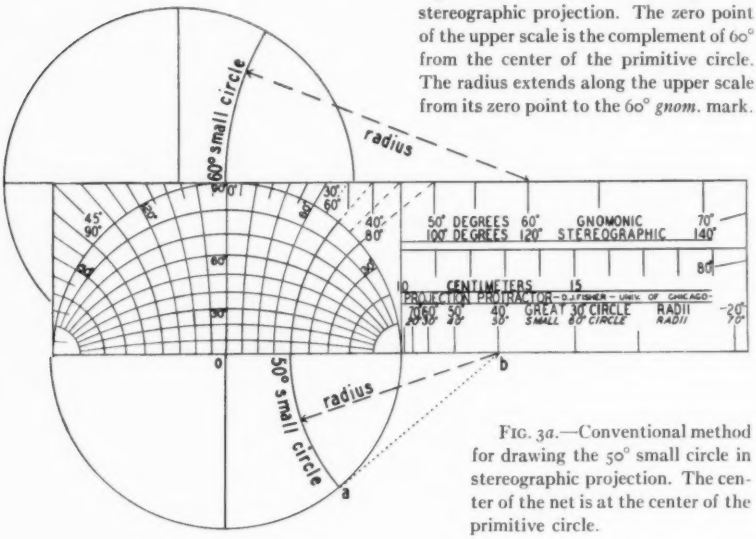


FIG. 3*a*.—Conventional method for drawing the 50° small circle in stereographic projection. The center of the net is at the center of the primitive circle.

value (*ab* of Fig. 3, *a* = *oc* of Fig. 4, *a*). In short, the lengths of the radii of the small circles and the distances to the center of the primitive (from the centers of the small circles) become the distances to the center and the lengths of the radii of the great circles of complementary value (*ob* of Fig. 3, *a* = *dc* of Fig. 4, *a*).

GNOMONIC PROJECTION

When points or lines on the surface of a transparent sphere observed by the eye held at the center of the sphere (here the center of projection) are plotted as they appear on a plane tangent to the sphere, the result is a gnomonic projection. This tangent plane (called

the "plane of projection") is of course normal to the line (the gnomon) joining its point of tangency and the eye or the center of the sphere. If the center C of the stereographic net (Fig. 2) be considered the center of a sphere of 5-cm. radius, and if the protractor is held so that the equator OC of the net is vertical, the upper scale of the

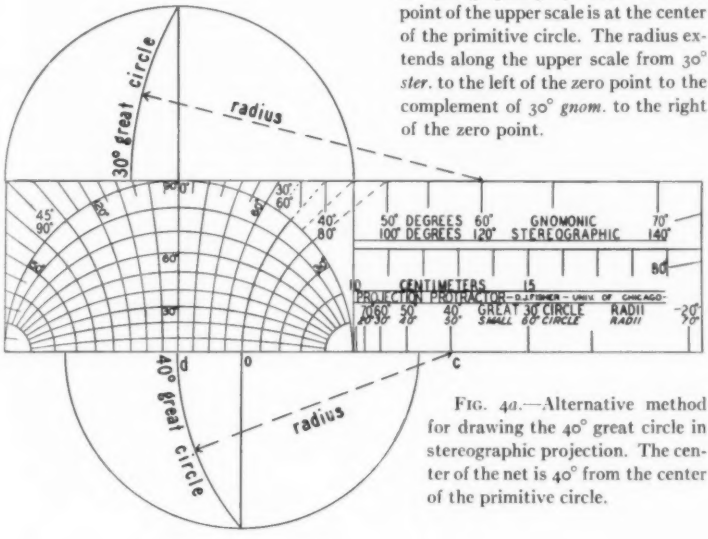


FIG. 4*b*.—Conventional method for drawing a great circle (30° in this case) in stereographic projection. The zero point of the upper scale is at the center of the primitive circle. The radius extends along the upper scale from 30° *ster*. to the left of the zero point to the complement of 30° *gnom*. to the right of the zero point.

FIG. 4*a*.—Alternative method for drawing the 40° great circle in stereographic projection. The center of the net is 40° from the center of the primitive circle.

protractor will then represent the trace of a horizontal, gnomonic, projection plane. With the eye at the center C of the net, on looking vertically up, the line of sight cuts the gnomonic plane at its zero point O. As the eye is inclined a varying amount off the vertical with the line of sight always remaining in the plane of the protractor, the graduations in gnomonic degrees along the upper scale of the protractor mark the points where the line of sight pierces the gnomonic plane at any given number of degrees from the vertical. The formula for this scale is $d = r \tan \rho$ where d = distance out from the zero point on the scale, $r = 5$ cm., and ρ is the angle made

by the line of sight with the vertical.[9] On this instrument gnomonic degrees along the top scale are thus the same as ordinary protractor readings.

It is, of course, possible to prepare a meridian gnomonic net similar to the stereographic net shown on the protractor.[10] On this the great circles are straight lines; the small circles normal to them are hyperbolas. Because of the limitations of the gnomonic projection already pointed out, this net is not regarded as of sufficient general utility to include it on the projection protractor.

THE TWO PROJECTIONS

It will be noted that any circle on the sphere is projected as a circle in the stereographic (really cyclographic) projection, although, if the original circle goes through the center of projection, its projection is a straight line. On the other hand, the great circles on the sphere appear as straight lines in the gnomonic (euthygraphic) projection. Small circles on the sphere become conic sections, such as circles, ellipses, parabolas, or hyperbolas in the gnomonic projection, depending on whether the plane of the circle is perpendicular to the gnomon or not; in the latter case it depends on whether the circle lies entirely within one hemisphere, tangent to the equator, or in both (upper and lower) hemispheres, where the equator is the great circle normal to the gnomon. It follows that many problems may be worked on the gnomonic projection using only straight lines. The construction is then relatively simple. On the other hand, the stereographic projection is angle true (conformal or orthomorphic); that is, where a couple of circles meet, one may draw their tangents and measure the true angle involved. The only true angles of the gnomonic projection are, in general, those whose apices lie at the center of the primitive. For this reason beginning students and others may have less trouble visualizing the stereographic projection. Therefore, the following problems are treated from this point of view first. The use of both projections drawn on a single sheet is shown to be

[9] The corresponding formula for the scale of stereographic degrees is $d = r \tan \rho/2$, as is readily inferred from the graduations; cf. Fig. 8.

[10] Such a net to 65° for a 4-cm. radius was prepared by Hilton in 1904, to 63° for a 5-cm. radius by Wright in 1911, and to 82° for a 7-mm. radius by R. W. G. Wyckoff in 1931 (*Structure of Crystals* [New York: Chemical Catalogue Co.], p. 143).

valuable in certain later problems. The projection protractor enables one to plot poles in both projections with great rapidity and accuracy. In connection with the following discussion the beginner is urged to carry out all operations called for by the instructions while actually reading them.

DISTANCE PROBLEM

(ANGULAR DISTANCE BETWEEN TWO POINTS)

For an initial illustrative problem is chosen an example related to everyday experience. Assuming the earth to be a sphere of radius such that 1° corresponds to just 69 miles,[11] what is the distance between point *v* of 35°49′ N. Lat. and 114°42′ W. Long. (in Arizona, 13 miles south of Boulder Dam) and point *t* of 40°49′ N. Lat. and on the zero meridian (in Teruel, Spain, 29 miles west of Tortosa)? The sphere with these points marked is shown in perspective in Figure 5, where dotted lines serve as projectors to carry them up to the plane of the gnomonic projection (at *V* and *T*) and down to the stereographic plane (at *V′* and *T′*). Just as we replace latitude by a ρ angle (= 90° − Lat. or colatitude for the northern hemisphere, 90° + Lat. for the southern hemisphere), we will use as azimuth a φ angle which is the same as the longitude for west longitude, but is equal to 360° − Long. for east longitude.

Stereographic solution.—Through the approximate center of a piece of typewriter-size paper, draw a line parallel the ends of the sheet. Place the protractor so that the polar axis of the net and the edge of the scale of small-circle radii lie along this line, with the center of the net (*C* of Fig. 2) near the center of the sheet of paper, which rests on a drawing-board, piece of cardboard, or several pieces of paper as a pad. The protractor is now in what is called its normal position. Using a sharp hard pencil draw short lines at both ends of the net's equator (consider the lower end as extended to the base of the projection protractor along the 81°15′ graduation of the r = 2 cm. gnomonic scale). Connect these lines, giving two straight lines meeting at right angles (at *C* of Fig. 6), and using their intersection as center describe the primitive circle of radius the same as

[11] This is the value for 1° of latitude at 40°. At the poles 1° of latitude = 69.41 miles; at the equator, 68.71 miles. 1° of longitude at the equator = 69.17 miles.

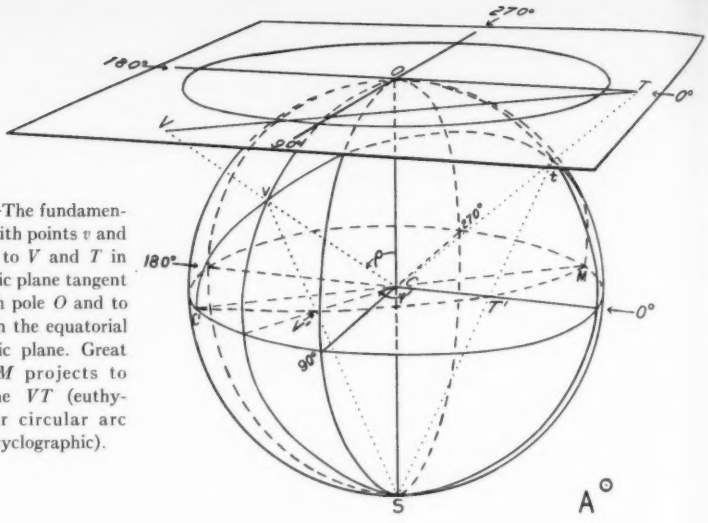


FIG. 5.—The fundamental sphere with points v and t projected to V and T in the gnomonic plane tangent at the north pole O and to V' and T' in the equatorial stereographic plane. Great circle $C'vtM$ projects to straight line VT (euthygraphic) or circular arc $C'V'T'M$ (cyclographic).

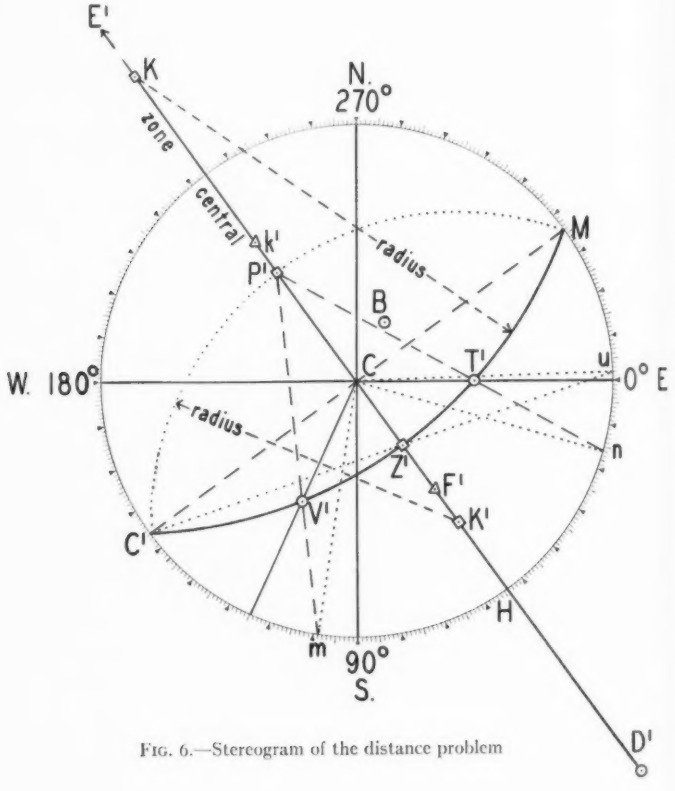


FIG. 6.—Stereogram of the distance problem

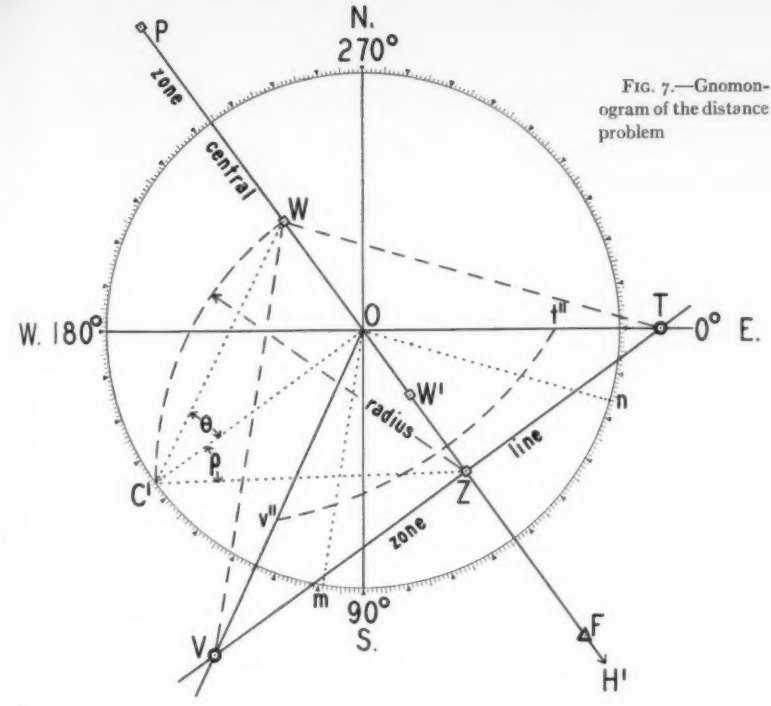


FIG. 7.—Gnomonogram of the distance problem

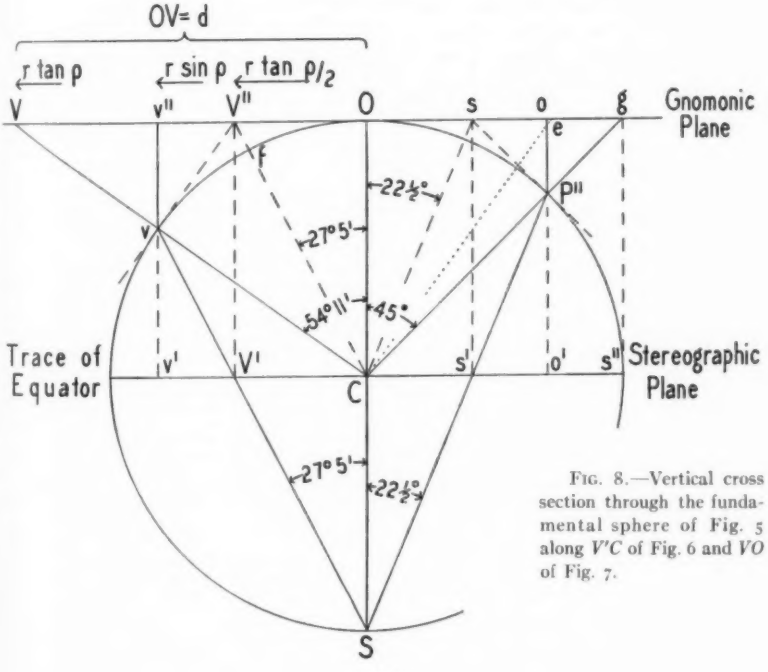


FIG. 8.—Vertical cross section through the fundamental sphere of Fig. 5 along *V'C* of Fig. 6 and *VO* of Fig. 7.

that of the net.[12] The line going out to the right represents the zero φ direction (corresponds to the meridian of Greenwich), and φ angles are measured clockwise from it as shown by the 90°, 180°, 270° marks of Figure 6. The center of the primitive circle represents the north pole of the earth in stereographic projection, and its circumference corresponds to the equator. In short, *our projection is being made with the eye 90° from the position in which it was when the net itself was made;*[13] that is, the surface of the upper hemisphere of the earth appears as projected onto the equatorial plane by sending all parts of it toward a focal point (the south pole, here the center of projection), and the eye is looking orthogonally down on this plane of projection. If the net of the projection protractor is considered as projected onto the plane of the equator, then its small circles represent vertical small circles on the sphere, and its great circles normal to them represent great circles on the sphere inclined at varying angles to the polar diameter and all passing through a single equatorial diameter.

Using the projection protractor as an ordinary protractor, lay off an azimuth or φ angle of 114°42′. In doing this put the protractor in its normal position and plot the diametrically-opposite direction of 294°42′. Now, placing the top scale with its zero point at the center of the circle (as in Fig. 4, *b*), lay off distances out from the center along this line and along the zero meridian corresponding to stereographic ρ angles of 54°11′ and 49°11′, locating points V' and T'.

[12] The original cross may be made more rapidly with a straight-edge and the projection protractor used as a right-angle triangle. For laying off φ angles a complete-circle protractor is time saving; with one of these one quickly locates the ends of the cross too. Or best of all, work on a piece of the new stabilized tracing paper which has the Penfield type of circular protractor (shown on the diagrams of this paper) of radius the same as that of the net all printed on it. Such forms on typewriter paper can be planographed at less than ½ cent each in 500 lots (cf. A. L. Parsons, *Amer. Min.*, Vol. XIX [1934], pp. 340–42). When points off this size paper happen to be needed, it is simple to attach an extra scrap of paper along the desired edge with the aid of Scotch cellulose tape. The actual drawing of the primitive circle is often dispensed with except in beginning work or where publishable diagrams are wanted.

[13] Of course the protractor might have been made with an equator (polar) stereographic net (like the one by the writer in the *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXII [1938], p. 1264), but the meridian one is much more valuable for our purposes, as will later be demonstrated.

Prick these points with a sharp, fine needle (whose head has been dipped in sealing wax) while looking through a low-power lens held in the left hand (or mounted on a support), which at the same time braces the projection protractor; surround the pricked points with tiny circles. By means of a scriber or mounted needle and working under a weak magnifying glass, carefully punch[14] a fine needle hole through the exact center of the net (*C* of Fig. 2) of the projection protractor. Next put the protractor accurately in its normal position and, placing the mounted needle (held between the right thumb and index finger) in the paper through the hole at the center of the net, with the left hand rotate the protractor clockwise about the needle as axis until the two points V' and T' lie under the same great circle of the net (in this case near the 34° circle). Read the angular distance between V' and T' along this great circle by counting the small circles of the net. This gives an answer of approximately $82\frac{1}{2}°$, which corresponds to about 5,693 miles.[15] Since $1'$ is equivalent to 1.15 miles, the accuracy of the result as stated in miles is approximately the same as that of the reading of the angular distance in minutes.

Alternatively, the angle between V' and T' could be read as the arc intercepted along the primitive circle by lines[16] from P' through

[14] Be careful to avoid parallax. Sight the needle while looking first in the direction of the polar axis of the net and then while looking in the equatorial direction. Similarly, punch a hole at the center of the $r = 2$ cm. net.

[15] This arc is really 82°46′, which corresponds to 5,711 miles on the assumption made. The true distance (taking the earth as a spheroid) is 5,733 miles.

[16] These lines represent the cyclographic projection of small circles on the sphere through *PvS* and *PtS* (Fig. 5, where *P*, the upper pole of *C′vtM*, is not shown). Since these circles go through the center of projection, they appear as straight lines. If *C′vtM* of Fig. 5 is reflected by a plane normal to these small circles and bisecting the angle between the plane of *C′vtM* and the plane of projection (and so normal to *PS*), it will go to the primitive; and points *v* and *t* will move by this same reflection to points corresponding to *m* and *n* of Fig. 6. The method of reflecting a random face-pole by a random plane is described under "reflection twin" near the end of this paper. The technique described above applies to the reflection of two or more random face-poles lying on a single great circle by a special plane, so that the reflected face-poles all lie on a special great circle, the primitive (cf. H. E. Boeke, *Die Anwendung der stereographischen Projektion* [Berlin: Gebrüder Borntraeger, 1911], p. 14).

The quickest and most accurate graphical method for locating P' from V' and T' without using a net is to find the point *K*, where the two lines of centers for V' and T'

V' and T' (Fig. 6) locating m and n. This method is particularly convenient when working with a graduated primitive circle (if the graduated circle does not have a 5-cm. radius, draw the lines Cm and Cn and if necessary extend them to it). The point P' is the pole of the circle $V'T'$; that is, it is 90° from any point on $V'T'$. It is located by noting that when a great circle of the net of the projection protractor lies along V' and T' (see above), this great circle is out just over 34° (CZ' of Fig. 6)[17] from the polar axis of the net and the equator of the net has an azimuth corresponding to φ of 54°. Mark the positions of both ends of the net equator (O and below C of Fig. 2) by short lines at H and near P' of Figure 6 and draw a line through these points. This is the line of measures for arc $V'T'$. Placing the upper scale along this line (in the manner of Fig. 4, *b*), locate P' by remembering that $CP' = 90 - CZ'$ (ster. degrees).

Figure 6 shows the arc of the great circle connecting V' and T'. It is not necessary to draw this to solve the problem, but for illustrative purposes it may be desirable to have it. Its center at K is found by holding the protractor along HP' as in Figure 4, *b* and plotting CK in gnomonic degrees as $90 - CZ'$ in stereographic degrees. The great circle $V'T'$ of radius $Z'K$ may now be drawn.

In looking at the stereogram (stereographic projection) of Figure 6 the eye is of course above the paper and is best considered as looking down orthogonally on it. One thus sees the equatorial plane of a sphere (Fig. 5) on which has been projected the upper half of the sphere by joining points, etc., on this hemisphere by means of straight lines called projectors with the south pole (directly below C of Fig. 6) and noting where these projectors cut the equatorial plane

---

intersect. Then on radius CK plot CP' in ster. degrees = CK in gnom. degrees. However, if points V' and T' are not over 30° from the center of the primitive, it is better to locate P' by the gnomonic construction given three paragraphs ahead.

An alternative method for measuring the angle between any two points as V' and T' is to locate the antipodal point A of either one of them, say V'. To do this place the top scale of the projection protractor along CV' with its zero point at C and lay off 180° ster. from V'. Draw the plane triangle $V'T'A$ and bisect $\angle V'T'A$ locating B on AV'. Then $T'V' = BV'$, and the latter distance is easily measured with the projection protractor held as it was to locate A.

[17] This angle may also be measured by counting the great circles along either small circle of the net going through V' and T'; or make CC' normal to $Z'P'$ locating C' and draw $C'Z'$ extended giving u and read $\angle MCu$ = arc Mu.

(plane of the paper). It is also possible to visualize the stereogram as sort of a perspective drawing. Thus $C'V'T'M$ may be thought of as a diametral plane of the upper hemisphere with an inclination or dip of $HZ' = 56°$ (visualized as $< V'C'm$) in the direction of CK with $\varphi = 234°$. Beginning workers will be aided by having handy a globe or blackboard sphere (dip a cheap globe in flat black paint) together with a circular cardboard protractor to fit it. If the student becomes able to look at a stereogram as though he were seeing a sphere, he will find little difficulty in graphically solving the ordinary problems of spherical trigonometry by means of this projection.

Gnomonic solution.—Using the projection protractor as an ordinary protractor, plot (as in Fig. 7) the co-ordinate axes and the $\varphi = 114°42'$ azimuth line, just as is previously described for the stereographic projection. Also add the primitive circle, the locus of all points for which $\rho = 45°$ gnom. Similarly locate V and T, except place these $54°11'$ and $49°11'$ out from O, using the gnomonic scale along the top of the protractor held as in Figure 4, *b*. Draw the great circle VT (called the zone-line); with a straight edge along it, erect a perpendicular ZW (called the zone-central or the line of measures) to it through O, using a right-angle triangle (or, since the projection protractor is rectangular in shape, it may be used for this purpose in lieu of a triangle). Z is called the zone-center. With the projection protractor top scale along OZ (with its zero point at O), read that $OZ = 34°10'$ (gnomonic scale). Without moving the protractor lay off $OW = (90 - 34°10') = 55°50'$ stereographic degrees locating W, the angle-point for the line VT. Draw VW and TW and measure $< VWT = 82\frac{1}{2}°$, the angular distance V to T. Of course if one is working on paper graduated with a divided circle, the lines VW and TW are not drawn; merely make a short line (parallel VW through O) at m on the divided circle by laying the hypotenuse of a triangle along V and W and then sliding the longer side of the triangle along a straight edge until the hypotenuse goes through O; proceed in analogous fashion to get the point n; the arc mn is the required answer.

This gnomonic solution is capable of greater mechanical accuracy than is that of Figure 6 and also enables one to locate the zone-

central ZW in simpler fashion. Having this, P' and K of Figure 6 may be quickly spotted with the projection protractor by the method already given, or K may be located by using triangles to erect a normal to $K'C'$ at C', where K' of Figure 6 corresponds to Z of Figure 7. With K (Fig. 6) as center and radius KC', an arc serves to locate V' and T' quickly. Thus gnomonic methods may be time saving and permit of greater accuracy in the location of stereographic poles or in the drawing of a great-circle arc passing through any two given nonantipodal points in the stereographic projection. Had the ρ value of point T been 90° instead of 49°11′ (that is, had point T lain on the equator at 0° Long.), line VT of Figure 7 would have been parallel the $0° - 180°$ φ line, and point Z would have lain on the 90° φ direction.

To visualize this problem, consider the gnomonogram in the plane of the paper as representing a sheet of glass tangent to the north pole of the earth at O (Fig. 5). One is looking orthogonally down on this sheet, in the direction of the axis of the earth. Thus O (Fig. 7) is directly above the center of the earth at C. This is shown in vertical cross section along the Boulder Dam meridian (OV of Fig. 7) in Figure 8, where v represents Boulder Dam. Point v on the sphere is projected to the plane of the paper as V if gnomonic, v'' if orthographic, and V'' (orthogonal projection from V') if stereographic. These relations are indicated on the right side of the drawing for a point P'' with ρ angle of 45°, where s, o, and g stand for stereographic, orthographic, and gnomonic projections of P''. Note that g for $\rho = 45°$ gnom. is at the same place as s'' for $\rho = 90°$ ster. Both lie on the primitive circle of their respective projections.

Thus looking down on Figure 7 one can visualize the plane $Vv''t''T$ which is a part of the plane VCT (where C is the center of the sphere and so directly below O of Fig. 7). If this plane is flapped up around VT as an axis so that C lies in the gnomonogram (the drawing or the gnomonic projection in the plane of the paper), it will reach point W. Hence $< VWT = < VCT$, the required angle between face-poles V and T. To see that W represents C rotated into the gnomonogram about VT, erect a normal to ZW at O (dotted line in Fig. 7), giving OC', where C' is on the primitive circle and corresponds to the center C rotated 90° about ZW as an axis. Draw

the dotted lines ZC' and WC' and consider $\Delta WZC'$ as part of a vertical section through the sphere. Then $ZC' = ZC$, and these $= ZW$; that is C, W, and C' lie on the same spherical shell (whose center is at Z). Call $\angle ZC'O = \angle ZCO = \rho$ (here $= 34°10'$) and $\angle WC'O = WCO = \theta$. Since $\Delta WZC'$ is isosceles, $\angle ZWC' = (\rho + \theta)$. Thus $\angle OZC' = 180 - 2(\rho + \theta)$ or $(90 - \rho) = 180 - 2(\rho + \theta)$ or $\theta = \frac{1}{2}(90 - \rho)$. Therefore, $OW = r \tan \frac{1}{2}(90 - \rho)$ which is the same as plotting $(90 - \rho)$ in stereographic degrees.

The angle point W for any zone-line VT is thus the center of the sphere rolled up about that line as axis into the plane of the gnomonogram. It permits one to measure the angle between any two face-poles on the zone-line with an ordinary protractor.

PROJECTION SYMBOLISM AND RELATIONS

In the gnomonic projection we may represent a plane by means of a point (called a "face-pole") where a line through the center of the fundamental sphere normal to the plane cuts the gnomonogram, or a line (called its euthygraphic[18] projection) which corresponds to the intersection with the gnomonogram of the plane in question, moved parallel itself until it cuts the center of the fundamental sphere. A face-pole in the gnomonogram is surrounded by a tiny circle if it corresponds to a face-pole on the upper half of the sphere, by a tiny triangle if on the lower half; if on the equator, it is represented by an arrow pointing toward it. Points which are not used primarily as face-poles, such as angle-points, may be surrounded by a small square. These relations are indicated in Figure 9, which represents a vertical section through Figure 7 along the zone-central PZ. In these two figures F corresponds to a point p' on the lower hemisphere projected gnomonically to F'' in a plane tangent to the sphere at the south pole S and then orthogonally to the plane of the paper or the regular gnomonic plane tangent to the sphere at its north pole O. A point on the equator (such as H, Fig. 9) is represented in the gnomonogram of Figure 7 as an arrow in the direction OZ toward H'; e.g., this points toward a face-pole in the given direction at infinite distance.

[18] Also known as the linear projection (of Federow). Not to be confused with the older linear projection of Quenstedt.

Since the symbol (e.g., as the Miller indices) of a crystal face is always put in parentheses, thus (*hkl*), where such a symbol so appears in the gnomonogram near a line, that line is known to represent the euthygraphic projection of the face in question; where it is near a point, the latter represents a face-pole. The pole of the euthygraphic projection of a plane (e.g., the pole of a line in the gnomonogram) corresponds to its gnomonic face-pole; that is, every point on the euthygraphic projection of a plane is 90° from its pole, just as on the earth each point on the equator is everywhere 90° from either pole.

A line or direction in space is represented by that point of the gnomonogram where it cuts the latter after being moved parallel itself until it goes through the center of the fundamental sphere. This is analogous to the euthygraphic projection of a plane. Of course in case the direction is parallel the gnomonogram, its projection is also a line (an arrow). If the direction represented corresponds to a zone-axis (edge-pole), the point is surrounded by a circle or triangle (as is true for a face-pole), but the symbol near it is put in brackets, thus [*uvw*]. A direction in space may also be represented in the gnomonogram by a line, which is the intersection of a plane through the center of the fundamental sphere normal to the direction in question with the gnomonogram. If such a line represents a zone-axis, it is called a "zone-line" and is indicated by a symbol in brackets. Thus, every point on a zone-line is 90° from the euthygraphic projection of the zone-axis, and the latter is the pole of the former. If one wishes to distinguish a plane cutting the lower hemisphere from one cutting the upper hemisphere, the lines used in the euthygraphic projection may be dashed and continuous; no such significance should be attached to the dashed lines of Figure 7.

In the stereographic projection, planes or directions may each be represented by points or lines, exactly as is true for the gnomonic, and the same symbolism may be employed (except the use of an arrow to represent a face-pole drops out). The stereogram of Figure 6 and its vertical cross section along the zone-central *KH* as shown in Figure 9 serve to bring out how poles are projected stereographically. Note that a point *p'* on the lower hemisphere is projected toward the north pole *O* onto the equatorial plane at *F'* which

is surrounded by a tiny triangle (Fig. 6) to show that it represents a point projected to the north pole. However, point p' (antipodal to p) on the sphere of Figure 9 may be projected stereographically to D' if to the south pole (shown as D' in a tiny circle in Fig. 6) or to F' if to the north pole (shown as F' in a tiny triangle in Fig. 6). Practically, if one needs to use not very much more than one hemisphere, it might be well to extend the stereographic projection outside of the primitive circle to such a point as D', simply to avoid the use of separate symbols to indicate points projected to O. When a plane normal to the plane of Figure 9 such as the one whose trace is ZC is projected stereographically from its trace (a great circle) on the sphere to the south pole, it gives the circular arc $C'V'T'M$ of Figure 6; such a mode of showing a plane is called the "cyclographic" projection. This bears the same relation to the stereographic as does the euthygraphic to the gnomonic.

When the stereographic projection plane is the equatorial plane of a certain sphere (Fig. 5) and the gnomonic is a plane tangent to the same sphere at its north pole O, as is assumed for the scales of the projection protractor, there are very close relations between the two. These are more easily seen if it be assumed that the stereographic projection plane is projected orthographically onto the gnomonic projection plane, as is indicated in Figure 9. The combined stereographic and gnomonic projections are shown in the gnomonostereogram of Figure 10. Thus for the zone line $V''T''$ ster. and VT gnom. and the zone-central ZP, it is clear that the gnomonic zone-center Z is at the same position as K' (Fig. 6), the center for the dotted-line great circle $C'P'M$ through the pole P' of the great circle $V'T'$. Similarly the zone-center Z' (Fig. 6) corresponds to the angle-point W' (Fig. 10) of a line (not drawn in Fig. 10) normal to ZP through P. W, the angle-point of zone-line VT, coincides with P' (Fig. 6), the pole of the great circle $V'T'$. Lastly, K (Fig. 6), the center of the great circle $V'T'$, is the same as P (Fig. 10), the pole of the zone-line VT. Figure 9 also shows that ZC and PC are normal to each other and how W and W' may be derived from arcs through C (or C' of Figs. 7 and 10) with centers at Z and P. Note that tangents to the sphere at p and z of Figure 9 also serve to locate W and W'; moreover, $<OCW = <WCP = \theta$ and similarly

$<OCW' = <W'CZ = \rho/2 = 45^\circ - \theta$. Thus OW in stereographic degrees = OP in gnomonic degrees; likewise OW' ster.° = OZ gnom.° and since $ZP = 90^\circ$ gnom. then WW' must = 90° ster. = 45° gnom. and $ZP = K'K = 180^\circ$ ster.

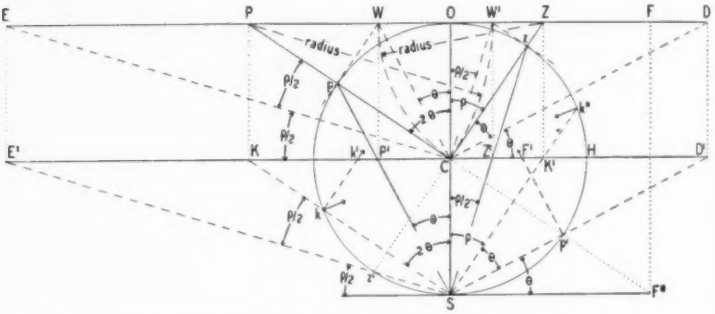


FIG. 9.—Vertical cross section through the fundamental sphere of Fig. 5 along the zone-central (line of measures) KK' of Fig. 6 and PZ of Fig. 7.

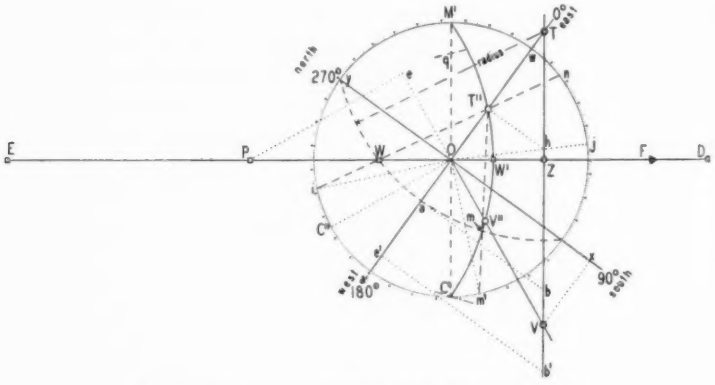


FIG. 10.—Gnomonostereogram of the distance problem

Figure 11 illustrates how these relations are taken advantage of in using the projection protractor to locate K', P', and K of Figure 6 (given Z' at 34° ster.) or W', W, and P of Figure 7 (given Z at 34° gnom.). These four are the "conjugate points" of Goldschmidt and

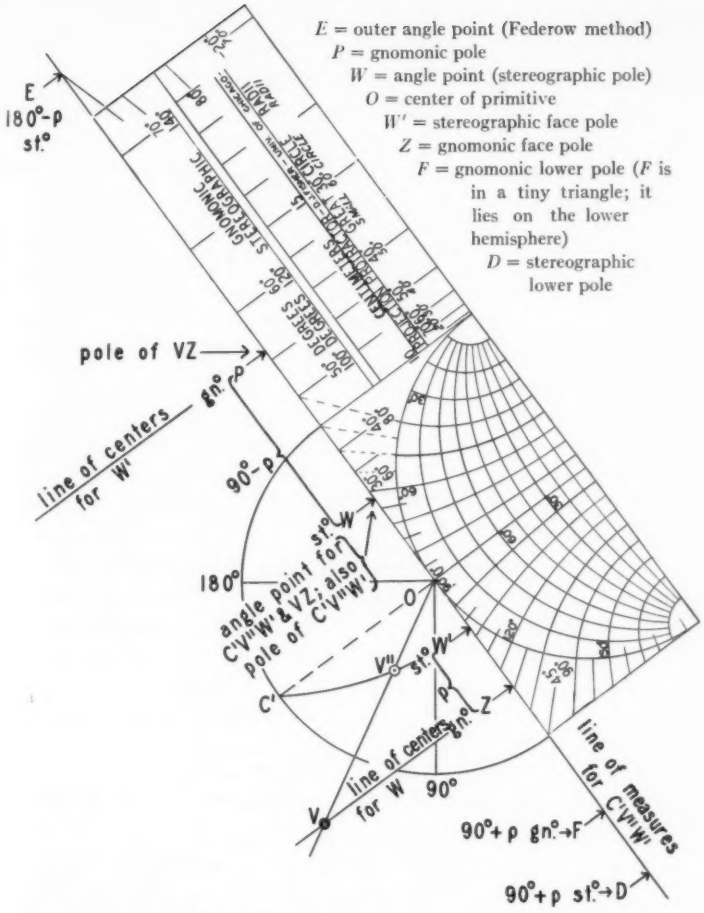


FIG. 11.—Method of location of conjugate points along a zone-central (line of measures) with the upper scale of the projection protractor. Here the face-pole (W' or Z) has a ρ value of 34° (and thus $\theta = 28°$, since $\rho + 2\theta = 90°$).

Boeke. TO (Fig. 10) is called the "line of centers" for point y, and VT is the line of centers for point W. That is, all great circles passing through y have their centers along the diameter TO extended and all through W have their centers along VT extended. The point T (the gnomonic pole of t, Fig. 5) at the intersection of the two lines of centers is thus the center for passing the arc of a great circle through y and W. Note in Figure 10 that $WZ = ZD$ where WD ($P'D'$ or WD of Fig. 9) = 180° ster. = 90° gnom.; thus $<ZC'D$ ($= <ZCD$ or $K'SD'$ of Fig. 9) $= \theta$. Similarly a line through P normal to $W'P$ is the line of centers for W'; and $W'P = PE$ where $W'E$ ($Z'E'$ or $W'E$ of Fig. 9) = 180° ster. = 90° gnom. and $<PC'E$ ($= <PCE$ or KSE' of Fig. 9) $= \rho/2$. Since WD = 180° ster., any great circle through W must also go through the antipodal point D; thus VZ, the perpendicular bisector of WD, is the locus of the centers of all great circles through W. Similar reasoning applies to $W'E$ and the line of centers for W' through P normal to $W'E$. The points D and E might also be embraced in the concept of conjugate points.[19]

If it is desired to show both stereographic and gnomonic face-poles on the same diagram, they may be distinguished by using light and heavy tiny circles (or tiny triangles), primed and ordinary letters, or different colors of ink. The curves of the cyclographic projection are easily distinguished from the straight lines of the euthygraphic; planes normal to the plane of the projection are represented by the same straight lines through the center of the projection plane in both projections. The one set of face-poles may be derived very rapidly from the other set with the projection protractor as shown in Figure 11. Ordinarily it is not necessary to distinguish the cyclographic from the stereographic or the euthygraphic from the gnomonic, since the symbolism or context of the explanation will make clear which is being used in any given case. It is necessary, however,

[19] Federow (*Zeitschr. Krist.*, Vol. XLIV [1908], top p. 91) made use of E to measure the angle between V and T, Fig. 10; the lines EV and ET locate C' and q on the diameter parallel VT; then with the upper scale of the projection protractor held along $C'q$ with the zero point at O, one reads the required angle between C' and q as $82\frac{1}{2}°$. Wright (*Amer. Min.*, Vol. XVII [1932], p. 426, case 2) also used points D and E in fixing his "common polar planes." For indexing spots in Laue photographs where the negative is 5 cm. from the crystal, if P marks the spot, then D is the pole of the reflecting plane in the gnomonic projection.

that the worker understand these conventions in order to visualize clearly the problem at hand.

When working with both stereographic and gnomonic projections on the same diagram, it is essential to consider the plane of the paper as the projection plane. This may be accomplished in any one of three ways. The simplest would seem to be to regard the stereogram as projected orthographically to the plane of the gnomonogram as has already been suggested. This same concept is here used in locating points on the lower half of the sphere in the gnomonogram. Another method is to have the paper lie in the equatorial plane of the sphere for the stereographic projection and to assume for the gnomonic a second sphere (of the same radius) centered at S of Figure 8 or 9 with SC as the gnomon. In this case points on the lower halves of both spheres should probably best be projected diametrically to the upper halves and then to the plane of the paper to avoid bringing in the orthographic concept. A third possibility is to have the paper in the gnomonic plane of Figures 8 and 9 and to derive the stereographic projection in this same plane from the spherical projection by lines tangent to the sphere at the spherical face-poles; each such line, however, must then lie in the plane of the point being projected and the gnomon CO. Tangents of this sort are shown by dashed lines in both Figures 8 and 9. So far as is known this concept is original, but it is not advocated here since it is too difficult for the beginning worker to visualize.

APPLICATIONS OF THE DISTANCE PROBLEM

Crystallography.—In terms of morphological crystallography the distance problem consists in finding the interfacial angle between the faces represented by face-poles v and t (Fig. 5) which correspond to $(1\bar{1}1)$ and (021) on fayalite (olivine). These two faces meet in an edge whose direction establishes the zone in which the two faces lie. This zone may be represented by its zone-line, the great circle $V''T''$ or VT of Figure 10, or by its zone-axis (edge-pole). The latter is the direction of the zone edge which is projected cyclographically (euthygraphically) as point $W(P)$,[20] the pole of the great circle

[20] Symbols in parentheses refer to the gnomonic projection, the others to the stereographic.

$V''T''(VT)$. $W(P)$ lies on OP 56° out from O or 90° from $W'(Z)$; it is easily located with the projection protractor placed as in Figure 4, *b*, along the line, as is shown by Figure 11. That W is 90° from any point on $V''T''$ is clearly seen if the net of the projection protractor is rotated on its center about a needle at O (as was done before) and degrees are counted along any great circle going through W. Visualizing the stereogram in perspective, one has no difficulty in picturing WO (where W is the projection of point p of Fig. 9 on the upper surface of the sphere, and O is the projection of the center C of the sphere) as a line normal to the $C'V''T''M'$ plane. The zone symbol $[uvw]$ is easily obtained from Figure 10 by Mallard's gnomonic method where Ox is taken as the unit co-ordinate on the a-axis and OT as twice the unit on the b-axis. The zone-line VT thus cuts these axes at $\frac{2}{3}$, 2. To their reciprocals add $\bar{1}$, giving $\frac{3}{2}\ \frac{1}{2}\ \bar{1}$ which on clearing of fractions yields the zone symbol $[31\bar{2}]$. Note that if a zone-line is parallel an axis, it cuts that axis at ∞, and $1/\infty = 0$. If the zone-line is a diameter of the primitive, find where a parallel line through unity on the $+a$-axis cuts the b-axis; take the reciprocal of this value for the second index and make the third index nought.

The zone symbol $[uvw]$ may also be derived from P, the pole of VT. To do this it is necessary to remember that the ordinary gnomonic projection is reciprocal, yielding by Cartesian co-ordinates the Miller indices (via the Goldschmidt indices), which themselves are reciprocals. But zone symbols are ordinary intercepts and not reciprocals. Thus one may use the euthygraphic projection (which is nonreciprocal) provided a suitable Cartesian grid is added in which the units parallel the a- and b-axes are respectively a_0r and b_0r, where a_0 and b_0 (given directly in Goldschmidt's *Winkeltabellen*) are axial ratio units when $c = 1$ (instead of having $b = 1$ as is customary), and r = the radius of the sphere of projection. If such a grid be added to Figure 10 (with $a_0 = 0.794$ and $b_0 = 1.727$) the co-ordinates of P are seen to be $\frac{3}{2}\ \frac{1}{2}$. Now add unity and clear of fractions giving $[\bar{3}\bar{1}2]$, which is the same zone symbol as $[31\bar{2}]$. Of course the zone symbol for a zone-line may also be obtained from the indices of any two face-poles lying on the line by the familiar methods of cross-multiplication (determinants).

Geology.—In solving problems in structural (mining, metamorphic) geology, consider the eye as at the zenith of the point of actual field observation and regard the primitive as if it were the divided circle of a compass held tangent to the earth (that is, horizontally) at this point.[21] The relation between compass directions and φ angles is then as follows:

	N	*E*	*S*	*W*
φ angle.....	270°	0°	90°	180°

Then $V''T''$ of Figure 10 (or VT) might represent the cyclographic (euthygraphic) projection of a bedding (joint, cleavage, vein, fault) surface dipping $< m'C'V'' = 56°$ (complement of $CZ' = < HCu =$ arc Hu of Fig. 6) to the N. 36° W. Its apparent dip to the west would then be 40°49′ (complement of OT'' ster. or of OT gnom., Fig. 10), and to the N. 24°42′ E. would be 35°49′ (complement of OV'' ster. or of OV gnom.). Or if these two apparent dips were read on adjoining vertical cliff or quarry walls trending in the directions given, the true dip of a bedding or fault-plane outcropping along them could be computed easily as 56° to N. 36° W.

These problems can also be handled simply on the gnomonic projection in terms of face-poles rather than according to the cyclographic-euthygraphic interpretation just given.[22] Thus P of Figure 10 may represent the face-pole of the dipping bed and then OP gives the direction and amount of true dip. Drop a perpendicular from P to VO extended locating e. Then $Oe = 35°49'$ represents the amount of dip (measured on the upper scale of the projection protractor held as in Fig. 4, *b*) in the direction Oe which is N. 24°42′ E. Note that e is 90° gnom. from V, as shown by angle $VC''e$, where

[21] As here developed, the upper hemisphere is projected to the equatorial plane. The writer (*op. cit.*, p. 1268) advocated projection of the lower hemisphere onto the equatorial plane, since this permits somewhat simpler visualization of the problems of structural geology; workers in petrofabrics regard this latter technique as standard practice. Which method is used makes little difference to the expert; the introduction of both here might be confusing to the beginner for whom this paper is prepared.

[22] Solution of these problems by means of the gnomonic projection corresponds to the use of tangents; by the euthygraphic, cotangents. Compare the author's "Some Dip Problems" in *op. cit.*, Vol. XXI (1937), pp. 341 and 348. The method of solution of the problem given in this article on the lower half of p. 349 is not true for the general case; the correct method appears in the same publication, Vol. XXII (1938), pp. 1261–71.

C'' is on a line normal to Ve through O. In Figure 8, e is just to the right of o, and $< VCe = 90°$. Of course e can also be located easily from V using the projection protractor as in Figure 11. A circle with OP (Fig. 10) as its diameter is the locus of all points such as e that are 90° along diameters of the primitive from the various points which can be considered as making up the line VT extended. Such a "curve of poles" in the stereographic projection is one of a family of complex curves not easily prepared. Similarly the euthygraphic projections of all the face-poles which lie on a given zone-line in the gnomonic projection meet at the pole of that line. Thus P could be located from V and T by using the projection protractor as in Figure 11 to establish e and e' (90° gnom. from V and T) and erecting normals to Ve at e and to Te' at e'. This is the method used by Harker.[23]

If in Figure 10 V represents in gnomonic projection the face-pole of a bed dipping 54° to S. 25° W. and T that of a bed dipping 49° due east, the two field observations having been made not far apart but on opposite sides of an evenly plunging anticline, then the latter pitches in direction and amount the value of OZ, or 34° to the S. 36° E.

Problems involving dips between about 20° and 70° can be handled well on the gnomonic projection of 5-cm. radius sphere; beyond the upper limit stereographic solutions are generally simpler, though by using the 2-cm. radius sphere (length of gnomon), it is possible in some cases to extend considerably the upper gnomonic limit given. When dealing only with gentle dips, one may use the gnomonic projection drawn for a sphere of $r = 50$ cm.; with steep dips the euthygraphic interpretation is generally satisfactory.

For the case of drifting continents, if at one time in the geologic past the north pole was at 34° N. Lat. and 126° W. Long. in terms of present co-ordinates (P' of Fig. 6), then the equator of that epoch went through the present sites of Boulder Dam (v) and Teruel (t). The stereographic projection has also been used for the elucidation of fault nomenclature and the resolution of faulting movements.[24]

[23] Given by M. K. Hubbert in *Bull. Amer. Assoc. Pet. Geol.*, Vol. XV (1931), pp. 285–86.

[24] See R. Sokol, *Geologisches Praktikum* (1927), pp. 198–99; also M. Morishita, "On the Graphic Method of Representing Faults and Strata," *Japanese Jour. Geol. & Geog.*, Vol. XV (1938), pp. 207–39.

Other sciences.—The example taken might also be likened to problems of navigation, seismology, or astronomy.[25] Solutions for analogous problems in cartography, perspective projection,[26] and many other fields may also follow these lines.

[*To be concluded*]

[25] Stereographic solutions of a number of these are given in the last chapter of Bullard and Kiernan's *Trigonometry* (1930). Similar problems appear on pp. 52–72 of O. S. Adams, "General Theory of Polyconic Projections," *U.S. Coast and Geodetic Surv. Special Pub. No. 57* (1934); and in F. W. Sohon, *The Stereographic Projection* (New York: Chemical Publishing Co., 1941).

[26] See Sokol, *op. cit.*, pp. 210–11.

DISCUSSION: THE THEORY OF GROUND-WATER MOTION

H. KRUTTER
Pennsylvania State College

I have noted with interest the article by M. King Hubbert on "The Theory of Ground-Water Motion" published as Part I of the November-December, 1940, number of the *Journal of Geology*. The main theme of this article appears to me to be concerned with the proper generalization of Darcy's law. One also gathers from this paper that the generalization has never before been stated properly and, therefore, never used correctly. The latest author on this subject, namely, M. Muskat, in his book *The Flow of Homogeneous Fluids through Porous Media* is also presented as incorrectly generalizing Darcy's law. I have had the pleasure of twice using Muskat's book as a text, and I should, therefore, like to point out the correctness of the treatment there, since one would gather from Hubbert's criticism that everything in Muskat's book is wrong because of the difference as to whether or not a velocity potential can be defined for a system with variable constants.

The correct generalization of Darcy's law for a medium for all cases of practical interest is given in equation (2), section 3.3, page 129, in Muskat's book.

Hubbert generalizes Muskat's equations to take into account variable density. However, no application of this generalization is made. Muskat then proceeds to introduce a potential in equation (3). This is apparently the point at which Hubbert disagrees with Muskat. I think it should have been obvious to the reader that this step could have been taken only if permeability and viscosity are constant. I know that when I presented this to my classes, I made the above observation. That any other interpretation could be made had not occurred to me until I read Hubbert's discussion. Likewise equation (1), section 3.4, page 131, is true only if permeability and viscosity are constant, and this follows from my remarks above. The error

of omission made by Muskat as given above does not have any real significance, as may be observed in the subsequent treatment throughout the book. Muskat has consistently used the correct statement of Darcy's law for every application.

For example, on page 145, in the last sentence in the paragraph, it is explicitly stated that the preceding equations, in which Φ is used, refer only to the case wherein the medium is isotropic and homogeneous. Again, on page 277, section 5.5., an anisotropic problem is treated properly. Then on page 685, in the discussion of gas-flow systems in media of variable permeability, equation (1) explicitly shows that the k should be to the left of the pressure gradients (gravity negligible in this problem). The most direct evidence that Muskat made no basic error in the use of Darcy's law or in its formulation lies in section 7.2, on pages 401–3. Here again in the treatment of media with variable permeability, k is put to the left of the pressure gradients. As a final proof, in an article by Muskat and Meres[1] the formulation of the gas-liquid–mixture problem shows that, where k is variable for any reason, velocities are given by $k\Delta p$ and not by $\Delta(kp)$ (gravity again negligible and viscosity taken as constant).

The whole question as to whether or not Darcy's law can be expressed in terms of a velocity potential is merely academic as long as one has the basic equations in terms of pressure gradients and gravity head with the permeability factor placed outside the gradient sign. The use of a velocity potential depends entirely upon the convenience in simplifying the notation. There is no suggestion throughout Muskat's book that a single potential function exists for a medium of nonuniform permeability. On the contrary, it is explicitly shown in chapter vii that where the medium is composed of regions of different permeability, each region of different but uniform permeability should be given separate solutions either for the pressure or for the potential function and that the several solutions must then be joined by the boundary conditions at the interfaces. Moreover, when the permeability of the medium varies continuously, the problem is solved in the book in terms of the pressure

[1] *Physics*, Vol. VII (1936), p. 346.

function with the permeability as a factor to the left of the gradients in a strictly correct form. The introduction of a velocity potential to include everything except the permeability would involve only a matter of convenience of notation and would in no way change the significance of the basic equations as actually used. In view of the manifold examples correctly treated of all the possible diverse situations of practical interest throughout Muskat's book it is difficult to understand how a misinterpretation could arise and that the impression should be gained that there is any basic error in the work. Among the many problems specifically treated in Muskat's book, Hubbert has not pointed out a single one for which the final solution is erroneous. Certainly if the fundamental formulas were incorrect, the analytical deductions based on such an erroneous formulation would be likewise in error.

THE THEORY OF GROUND-WATER MOTION
A REPLY

M. KING HUBBERT
35 West Twentieth Street, New York City

In the introductory paragraphs of the paper which his critic discusses, reference was made by the present author to the earlier analytical studies of this subject, among which was cited the outstanding treatise, *The Flow of Homogeneous Fluids through Porous Media*, by Morris Muskat. With respect to these earlier works the following remark was made:

"While the importance of these and similar works cannot be overestimated, they have all fallen short in one or more important respects of the goal of establishing a theory of ground-water motion which is both free from internal contradictions and in conformity with all the fundamental principles of physics which ground-water motion must satisfy."[1]

Later, after a generalization of Darcy's law had been developed from first principles, it was shown that, of the several expressions for that law developed by Muskat, one was erroneous and another valid only in one important special case.[2]

Since no other references of a critical nature to Muskat's work were made, the foregoing must be the statements upon which the author's critic bases his discussion. To settle the points he raises let us, therefore, examine the record. For this purpose the sections of Muskat's book which embody the logical sequence, and are therefore the pertinent ones, are chapters ii, iii, and vii.

In chapter ii, entitled "Darcy's Law and the Measurement of Permeability," Muskat begins by stating Darcy's law correctly in the form:[3]

$$Q = \frac{cA\Delta h}{L}.$$

[1] *Jour. Geol.*, Vol. XLVIII, Part I (1940), p. 786.

[2] *Ibid.*, pp. 903–9.

[3] Eq. (1), p. 56.

Immediately afterward, however, he drops the hydraulic gradient factor, $\Delta h/L$, and subsequently confines himself to expressions involving the pressure gradient, dp/ds, only, arriving finally at the result,[4]

$$v = \frac{k}{\mu}\frac{dp}{ds},$$

as a formulation of Darcy's law. In the same chapter several figures depicting permeability apparatus are shown with flow in the vertical direction—an arrangement verified by the text. In some of these the fluids used were liquids.

Since these experimental conditions forbid the neglect of gravity and of the density of the fluid, the conclusion is inescapable that the expression for Darcy's law developed in this chapter is physically erroneous[5]—a conclusion that cannot be invalidated by the insertion of escape clauses to the effect that gravity is being neglected. Darcy's law is a description of experiments performed upon the earth, and it is not permissible to neglect gravity under such circumstances. Yet the foregoing equation has become one of the most widely used expressions for Darcy's law in the current literature.

In chapter iii, entitled "General Hydrodynamical Equations for the Flow of Fluids through Porous Media," a further attempt at generalization is made in which gravity is explicitly taken into account. This approach is culminated by the introduction of the velocity potential,[6]

$$\Phi = \frac{k}{\mu}(p - V),$$

where k is the permeability, μ the fluid viscosity, p the pressure, and V the gravity potential. From this the expression for Darcy's law,[7]

$$\bar{v} = -\nabla\Phi,$$

is obtained, about which Muskat makes the statement: "Equations (3) and (5) may be considered as the 'generalized Darcy's law,' and may be taken as the *dynamical* basis for all problems of viscous flow through porous media for all types of *homogeneous* fluids."[8]

This was the equation which the present author showed to be

[4] Eq. (3), p. 71.
[5] Hubbert, *op. cit.*, pp. 792–94.
[6] Eq. (3), p. 128.
[7] Eq. (5), p. 128.
[8] *Op. cit.*, p. 129.

valid only for the flow of a fluid of constant density and viscosity through a homogeneous and isotropic medium, and hence not a general expression of Darcy's law.[9] This, as my critic points out, was admitted later in the book by Muskat[10] himself.

Toward the end of chapter iii, the analogy between the conduction of heat and electricity, electrostatics, etc., and of the flow of fluids through porous media is stressed and analogous quantities tabulated in Table 13. Here again, for fluids, the pressure p is stated to be analogous to potential in electricity, yet the analogy is automatically invalidated by the further statement that gravity is being neglected, leaving us with no analogy at all.

Since the "generalized Darcy's law" of chapter iii is not valid for inhomogeneous media, the problem of the flow across the interface between two media of different permeabilities assumes a particular significance. How may this problem be solved? In chapter vii Muskat treats it as follows:

"Solutions of Laplace's equation are assumed for each region separately and then these are adjusted at the boundaries separating the regions—the 'surfaces of discontinuity'—so that the combined set of solutions corresponds to the combined fluid system. This 'adjustment' may be formulated more precisely by the following two conditions that must be satisfied at any surface of discontinuity separating two regions (1) and (2):

$$p(1) = p(2)\,, \tag{1}$$

$$k_1 \frac{\partial p(1)}{\partial n} = k_2 \frac{\partial p(2)}{\partial n}\,, \tag{2}$$

at all points of the boundary, the normal to which is indicated by n,"[11]

In a footnote he shows further that equations (1) and (2) yield a tangent law of refraction. Of these two equations, (1) is correct. Equation (2), however, is a reversion to the pressure-gradient form of Darcy's law of chapter ii, which has already been shown to be incorrect. As far as the tangent law of refraction is concerned, it is simply the mathematical consequence of any pair of equations of

[9] *Op. cit.*, pp. 903–9. [10] *Op. cit.*, p. 145. [11] *Ibid.*, pp. 400–401.

the form of (1) and (2). In fact, if we replace pressure by temperature in those equations, we still obtain a tangent law of refraction.

These instances should suffice to validate the author's original statement that the efforts of Muskat at formulating a proper generalization of Darcy's law were neither free from internal contradictions nor at all times in conformity with the fundamental principles of physics which such a law must satisfy.

As to the question of whether Muskat's calculations of specific problems are correct, the author can say only that this has been outside the scope of the present investigation but that he has never assumed, and certainly never stated, that the results were other than correct. Assuming that they are correct, then, with regard to the further question of how could correct answers to particular problems be obtained if errors in fundamental theory had been committed, the answer appears obvious enough—by not using the errors committed!

Cursory examination, including those passages cited by the author's critic, appears to indicate this to have been the case. For problems where his "generalized Darcy's law" was inapplicable, Muskat was obliged to fall back upon more primitive, but more general and exceptionless, physical equations:[12]

$$v_x = -\frac{k}{\mu}\frac{\partial p}{\partial x},$$

$$v_y = -\frac{k}{\mu}\frac{\partial p}{\partial y},$$

$$v_z = -\frac{k}{\mu}\frac{\partial p}{\partial z} + \frac{k}{\mu}\gamma g,$$

which, essentially, are those developed and used originally by C. S. Slichter.[13] These really are a generalized form of Darcy's law and are obtainable from the equations developed by the present author by differentiation with respect to the three co-ordinates. Furthermore, they contradict Muskat's avowed efforts at generalization in precisely the manner herein indicated.

[12] Eq. (1), p. 402.

[13] "Theoretical Investigation of the Motion of Ground Water," *19th Ann. Rept. U.S. Geol. Surv.*, Part II (1897–98), pp. 295–384.

REVIEWS

The Mammalian Fauna of the White River Oligocene. By WILLIAM BERRYMAN SCOTT and GLENN LOWELL JEPSEN. Part III: *Lagomorpha.* By ALBERT ELMER WOOD. Part IV: *Artiodactyla.* By WILLIAM BERRYMAN SCOTT. (*Transactions of the American Philosophical Society*, Vol. XXVIII [new ser., 1940].) Part III, pp. 271–362; figs. 45; pls. 2. Part IV, pp. 363–746; figs 19; pls. 44.

Part III of this series dealing with the mammalian fauna of the White River Oligocene is an excellent treatise on a group of mammals which presents unusual difficulties for study—the Lagomorpha. Wood considers this group to be of ordinal rank, following the procedure of several of his predecessors in the field, and offers supporting evidence sufficient to establish the rank beyond reasonable doubt. He feels that in all probability the resemblances of the lagomorphs to the rodents are the result of parallel development but admits the possibility that the two orders arose from a common, but primitive, ancestral stock which was somewhat removed from the basal stock of all placental orders.

Three genera are recognized as members of the White River fauna, namely, *Paleolagus*, *Megalagus*, and *Desmatalagus*. These and their species are described in detail and comparisons of genera are made. The descriptions are clear and are supported by illustrations so that they are intelligible to one not specifically acquainted with the field. The possibility that a fourth genus, *Archaeolagus*, may have existed in the Oligocene is mentioned, but the author is of the opinion that no specimens actually pertaining to this genus have as yet been found.

A discussion section is devoted chiefly to a technical consideration of the cusp homologies of the cheek dentition of the lagomorphs. Ehik's interpretations are considered. The author is in essential agreement with Ehik concerning the homologies within the order but disagrees with his attempts to draw homologies between orders. A diagram of cusp homologies as conceived by Burke, Ehik, and Wood is included. A portion of the discussion section is devoted to a consideration of the evolution of the lagomorph dentition and another section to comments on the relationships of the lagomorphs to other orders of mammals. The author reaches the conclusion that the lagomorphs have had an evolution separate from that of other orders since the Paleocene and possibly since the late Mesozoic. A distribution chart and a short discussion of the phylogeny of the order close the report.

The major portion of Part IV comprises descriptions of genera and species of the Artiodactyla. Each category of supra-specific level is defined in some detail, and each species receives a concise but full consideration, important measurements of a large number of specimens being included. A discussion of the geological and geographical ranges of representatives of various categories supplements the descriptive sections. The running style used for description makes for readability and enhances the value of the publication for nonspecialists in the field.

A most interesting feature of the report is the classification of the White River artiodactyls as presented in the Introduction and supplemented in considerations of the subordinal groups. Scott follows the usual scheme of separating the artiodactyls into two sections—the non-Ruminantia and the Ruminantia. Included in the first section are three suborders: the Palaeonodonta, the Ancodonta, and the Suina; in the second there is but a single suborder of White River artiodactyls: the Tylopoda. This grouping, proposed by Scott in an earlier publication, is justified by the author on the basis of similarities of the three superfamilies—the Hypertraguloidea, the Cameloidea, and the Oreodontoidea—in the Uinta Eocene, and because they appear to represent a North American radiation of the ruminants in contrast to the Old World radiation of the Pecora. The Hypertragulidae is divided into three subfamilies—the Hypertragulinae, the Hypisodontinae, and the Leptomerycinae—on the basis of nearly complete skeletons representing each division. At least three tribes of camels are recognized, but the relationship of each to later forms is not fully understood. Scott uses Gill's term, "Oreodontoidea," to refer to *Merycoidodon*, *Agriochoerus*, and related forms.

In keeping with the author's efforts to confine this series of reports to White River forms, there is little general discussion outside of that concerning problems of classification. More information of a general nature is to be found in Part III than in Part IV. The two volumes fulfil their purposes adequately and represent important contributions to the literature on faunas of the North American Oligocene.

EVERETT C. OLSON

Sedimentary Petrography. By HENRY B. MILNER. 3d ed. London: T. Murby & Co., 1940. (Distributed by Nordeman Pub. Co., New York.) Pp. xiii+666; figs. 100; pls. 52. $10.00.

The third edition of Milner's classic volume represents a complete revision of the previous edition, which was issued in 1929. In the decade which elapsed between the two editions, the science of sedimentary petrol-

ogy showed a marked development. The author has reflected this development in the added space devoted to the newer aspects of the science, especially as they concern laboratory methods. In comparison with the second edition, the revision marks a decided improvement in the discussion of such topics as sampling, mechanical analysis, and laboratory techniques in general. Additional topics which are new to the book or which have been expanded are X-ray and spectrum methods of mineral analysis, the microscopic analysis of sediments, and methods of testing sedimentary rocks. This last section includes the measurement of numerous mass properties, such as cohesiveness, water content, porosity, and permeability. The added detail in which such topics are treated may be realized from the fact that the new edition devotes 215 pages to the subject of laboratory analysis, whereas the earlier edition had only 115 pages.

Despite the improved treatment of many topics, some important subjects are touched upon only briefly. There is no adequate discussion of the distinction between shape and roundness, and the discussion of graphic methods of treating data does not extend beyond a few empirical measures for describing cumulative curves. The treatment of quantitative mineral frequencies receives some attention, and Dryden's important work in this respect is discussed in detail. Fortunately some of the topics only lightly touched upon are included in comprehensive bibliographies.

Milner's text is directed largely toward the application of sedimentary methods to the solution of oil-field problems, but theoretical aspects of the subject are not stinted. An important innovation of the new volume is a complete chapter devoted to the application of sedimentary methods to a wide variety of fields, including cement, ceramics, criminology, glass, highway construction, medicine, and refractories. This chapter (xv) covers material which should generally have more emphasis from sedimentary petrologists, because it represents important technological applications of essentially geological techniques. Milner devotes some fifty pages to the subject and includes well-rounded bibliographies on the separate topics.

The study of detrital minerals receives considerable attention from the author. In general organization this section is similar to the previous edition, but the list of minerals described has been essentially doubled. Additional plates illustrating detrital grains also mark an improvement over the earlier edition. The section on the petrography of consolidated sediments is treated in approximately the same detail as before, as is the section on petrographic correlation.

The format of the volume has been increased slightly, with considerable improvement in appearance. In addition to the larger size of the

pages, the total number of pages has been increased from 514 to 666. In all respects the new edition carries forward the tradition of earlier editions, and it bids fair to hold its position as one of the most widely used reference books in the field.

W. C. KRUMBEIN

Some Principles of Accelerated Stream and Valley Sedimentation. By STAFFORD C. HAPP, GORDON RITTENHOUSE, and G. C. DOBSON. (Technical Bull. 695.) Washington: Department of Agriculture, 1940. Pp. 134; pls. 16; figs. 19. $0.75.

As early as 1908 Chamberlin (*Soil Wastage: Proceedings of a Conference of Governors in the White House, May 13–15, 1908* [60th Cong., 2d sess., House Doc. 1425]) recognized accelerated stream and valley sedimentation as a national problem. In the more than thirty years which have since elapsed the problem has become more acute. Unless conservation measures are adopted, it will become still more serious in the future, for the chief effects have not yet manifested themselves in the main trunks and valleys. This bulletin has been written to point out the various aspects of the subject, the nature and scope of the problem have been outlined, results of detailed studies in Tobitubby and Hurricane valleys of northern Mississippi are reported, and forty-five principles have been presented with explanatory discussions. Each principle has been presented as a statement of fact and is based chiefly on the detailed studies of this report. It is recognized that these principles may require extension and revision with further increase of knowledge.

The detailed studies of Tobitubby and Hurricane valleys show that during the one-hundred years of cultivation an average thickness of at least 5.4 inches has been eroded from the uplands. As a result of this erosion (most of the products having been deposited close to their source), 27.7 per cent of the valley land has been damaged by overwash of sand or by swamping, and an additional 32.1 per cent is of little value because of frequent flooding. Damage is due chiefly to (1) loss of productivity, (2) increase of flood danger, and (3) impairment of artificial structures.

Most of the modern sediments belong to four distinct genetic types, but at least two other types are present. These six types are: (1) channel-fill deposits, (2) vertical accretion deposits, (3) flood-plain splays, (4) colluvial deposits, (5) lateral accretion deposits, and (6) channel-lag deposits. These genetic types occur in four distinct associations, as follows: (*a*) normal flood plains or valley-flat associations, (*b*) alluvial-fan or alluvial-cone deposits, (*c*) valley-plug associations, and (*d*) delta associations.

Most geologists have some familiarity with Gilbert's investigation of the results of hydraulicking in the Sierra Nevada (*Hydraulic-Mining Debris in the Sierra Nevada* [U.S. Geol. Surv. Prof. Paper 105], 1917), but few are aware of the body of literature on the subject of accelerated sedimentation. The authors have examined a large portion of this literature and drawn heavily on it in the derivation of the principles they list. Because of its detailed character this report will doubtless serve as a model for future intensive investigations. The illustrations are well chosen and well reproduced.

C. W. STERNBERG

Geophysical Prospecting for Oil. By L. L. NETTLETON. New York: McGraw-Hill Book Co., Inc., 1940. Pp. 444; figs. 177. $5.00.

For some years now students of geophysics have felt the great need of a text which would present a composite picture of the principles and practices of modern prospecting by geophysical methods. Dr. Nettleton's book is a welcomed answer to this urgency.

The book is divided into five main parts. In the first four parts are discussed (1) gravitational, (2) magnetic, (3) seismic, and (4) electrical methods, while the fifth part deals with geophysical interpretation. In the discussion of each method are incorporated the physical laws and principles involved in the method, the instruments and field technique employed, the actual results achieved, and the geologic interpretations and limitations. Thus the book will be of interest and assistance to physicist, geologist, and specialized geophysicist alike.

The author has included a large number of diagrams which greatly clarify the principles involved and also numerous photographs of instruments and apparatus which give the reader a picture of actual field operations. Of the former, those diagrams illustrating the principles of various types of gravimeters, as well as those incident to the theory of the torsion balance, are especially helpful.

In a carefully selected Bibliography are given references to all of the important literature on geophysical-prospecting methods.

KENNETH L. COOK

Metamorphism in the Lake Wakatipu Region, Western Otago, New Zealand. By C. OSBORNE HUTTON. Wellington: Department of Scientific and Industrial Research, Geological Memoir No. 5, 1940. Pp. 84; pls. 17; figs. 17. 6*s*.

The region discussed in this report comprises about one thousand square miles of mountainous country in the Province of Otago. The

higher peaks bear permanent ice and snow, and the region is deeply dissected by ten rivers. Except where covered with limited sheets of Pleistocene or Recent alluvium, or the even more restricted mid-Tertiary sediments, metamorphic rocks crop out over practically the entire area. The petrology of the metamorphic rocks derived from quartzo-feldspathic sediments is the chief subject of the report.

Southwestern New Zealand furnishes an example of progressive regional metamorphism, although not on so complete a scale as that in the Scottish Highlands. Metamorphic zones for rocks of quartzo-feldspathic composition have been defined and listed in order of increasing metamorphism. These zones are (1) quartz-albite-epidote-sericite-chlorite, (2) quartz-albite-biotite-clinozoistite-muscovite, and (3) quartz-oligoclase-biotite-muscovite zone. In the Lake Wakatipu region four subzones of the chlorite zone have been recognized. These subzones show progressive metamorphism, and their boundaries are sharply defined by faulting. This metamorphism is attributed to low-angle thrust faulting, involving intensive shearing but without great temperature rise. So much tourmaline is present that the author thinks it to be of pneumatolytic origin, which would indicate contemporaneous invasion of deep-seated granitic masses. In the western section basic and ultrabasic masses have intruded the schists in several places. Consensus of opinion holds that there was a single period of intense metamorphism in Permian or early Triassic time.

This is a well-illustrated and ably written report which should be of value to petrologists and structural geologists.

C. W. STERNBERG

Minerals Yearbook 1940, Review of 1939. Compiled by H. HERBERT HUGHES. Washington: United States Bureau of Mines. Pp. x+1514. $2.00.

The current volume of this annual sets forth the record of trends and developments of the mineral industries in the United States during 1939 through statistical details and their analysis.

C. W. STERNBERG